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(MM-0101)

Evaluation of Airborne Electromagnetic Systems for Detection and Characterization of Unexploded Ordnance (UXO)

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AGL	above ground level
BBR	Badlands Bombing Range
BRAC	base realignment and closure
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CTT	closed, transferred, and transferring
DGPS	differential global positioning system
DoD	Department of Defense
DOE	Department of Energy
DQO	data quality objective
EE/CA	engineering evaluation/cost assessment
EM	electromagnetic
EOD	explosive ordnance disposal
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FAA	Federal Aviation Administration
FAC	Federal Acquisition Cost
FP	false positive
FUDS	formerly used defense sites
GPS	global positioning system
HAZWOPR	Hazardous Waste Operations and Emergency Response
HE	high explosive
ISMS	Integrated Safety Management System
MTADS	Multi-Sensor Towed Array Detection System
NAD 83	North American Datum 1983
NRL	Naval Research Laboratory
ORAGS-EMP	Oak Ridge Airborne Geophysical System—electromagnetic prototype
ORAGS-TEM	Oak Ridge Airborne Geophysical System—time-domain electromagnetic
ORNL	Oak Ridge National Laboratory
Pd	probability of detection
QA	quality assurance
QC	quality control

ACRONYMS AND ABBREVIATIONS (continued)

SNR	signal-to-noise ratio
STC	Supplementary Type Certificate
TEM	time-domain electromagnetic induction
USAESCH	U.S. Army Engineering and Support Center, Huntsville
UXO	Unexploded Ordnance
WFO	work-for-others (program)

Technical material contained in this report has been approved for public release.

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

As a result of past military training and weapons-testing activities, an estimated 6 million hectares (approximately 15 million acres) of U.S. land is potentially contaminated with unexploded ordnance (UXO) and/or weapons testing- and training-related artifacts. These contaminated areas include sites designated for base realignment and closure (BRAC) and formerly used defense sites (FUDS). Using current technologies, the costs associated with detection, identification, and mapping of this contamination has been estimated to be in the tens of billions of dollars. Current surface-based technologies have shown improvements in the ability to detect subsurface UXO but are unable to reliably discriminate UXO from other items that pose no risk. These approaches are generally labor-intensive, slow, and expensive. Significant cost savings could be achieved if it is demonstrated that advanced airborne methods can provide a substitute for a portion of the surface-based applications.

The airborne system demonstrated and evaluated for this project was based on a single transmitter coil and two receiver coils mounted on a rigid 12m x 3m rectangular boom structure that was mounted to the airframe of a commercial helicopter. Ancillary equipment included a laser altimeter and a real-time differentially corrected global positioning system (GPS) for navigation and data positioning. This configuration enabled operation at a nominal flight altitude of 1 to 3 meters above ground level (AGL). The survey methodology consisted of parallel lines traversing the areas of interest so that data were collected for each flight line at nominal data spacing. The survey process concludes with data processing, analysis, interpretation, and mapping using commercial software to generate digital images depicting locations and magnitudes of anomalies that may represent UXO.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objective of this project was to evaluate an airborne-based, high-resolution time-domain electromagnetic (TEM) system for the detection and mapping of probable UXO-related contamination. This technology, in turn, will be used to support the overall remediation of UXO contamination at Department of Defense (DoD) sites across the United States. This objective was based on validating detection and characterization of ordnance and ordnance-related debris at a large, previously surveyed area and at a controlled test site. Through the use of the airborne-based system on known sites, namely thoroughly documented test sites, these evaluation surveys produced results confirming that this technology is both practical and cost-effective for detection and mapping of UXO as well as wide-area surveillance associated with footprint reduction activities.

1.3 REGULATORY DRIVERS

No specific regulatory drivers influenced this technology demonstration. UXO-related activity is generally conducted under Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) authority. A draft Environmental Protection Agency (EPA) policy related to UXO is currently under review. Regardless of a lack of specific regulatory drivers, many DoD sites and installations are aggressively pursuing innovative technologies to address a variety of issues associated with ordnance and ordnance-related artifacts (e.g., burial sites) that resulted from weapons testing and/or training activities. These issues include footprint reduction and site characterization, areas of particular focus for this technology demonstration. In many cases, the prevailing concerns at these sites become a focus for the application of innovative technologies in advance of anticipated future regulatory drivers and mandates.

1.4 DEMONSTRATION RESULTS

To validate the detection capabilities of the system, several controlled test sites (Calibration Sites) developed under previous Environmental Security Technology Certification Program (ESTCP)-funded projects were surveyed in addition to surveys conducted on actual UXO-contaminated sites at Badlands Bombing Range (BBR), South Dakota. Seeded items included engineering items, inert ordnance, and simulants that were selected to bracket the expected detection parameters of the system. Actual ordnance items at the survey sites represented a limited range of ordnance, including M38 practice bombs, 2.25-in. rockets, and 2.75-in. rockets. Under favorable field conditions, the Oak Ridge Airborne Geophysical System—time-domain electromagnetic (ORAGS-TEM) was able to detect ordnance items as small as were detectable with the more mature helicopter total magnetic field system, i.e. 60-mm rounds. In field operation, we anticipate that a smaller percentage of 60-mm rounds would be detected, and that this sensitivity would be even more altitude-dependent than for magnetometer systems. The best ORAGS-TEM test grid results were considerably better than the results from the proof-of-concept Oak Ridge Airborne Geophysical System—electromagnetic prototype (ORAGS-EMP). At survey altitudes below 1.5m, the small multiple turn receiver coils in the vertical gradient configuration produced the highest signal-to-noise over most ordnance, but the advantage of the gradient configuration was lost at higher survey heights because gradient fields decay more rapidly than single coil responses. Furthermore, the large 3-m x 3-m receiver loop produced equivalent or higher signal-to-noise than the small coils at a 3m survey altitude. Peak target responses attenuated quickly with height (r^{-6}) and varied slightly depending on electromagnetic (EM) fields decayed at spatial rates between R-2 and R^{-6} according to the height of the survey, the transmitter-receiver configuration used, and whether or not gradient data were considered. Responses from ordnance measured at a 3m survey altitude dropped below background for most mid- and small-sized ordnance, irrespective of transmitter-receiver configuration.

1.5 STAKEHOLDER/END-USER ISSUES

Issues related to this demonstration project center on the appropriate use of the technology. Clearly, the improved airborne system is unable to detect all UXO items of potential interest, which is also true of ground-based systems. The technology continues to be constrained by the presence of tall vegetation and severe terrain that increases the distance between the system and the UXO items of interest, thereby limiting detection ability. It remains apparent that application of the technology to small survey areas will not be cost-effective due to the large cost associated with mobilization/demobilization and considerable helicopter costs. Users should consider both the intended UXO targets and survey area (size, terrain, and vegetation) before considering the use of airborne systems for UXO detection, mapping, or footprint reduction.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

With an estimated 6 million hectares (approximately 15 million acres) of U.S. land potentially contaminated with UXO or weapons-testing related artifacts, the costs associated with the detection, identification, and appropriate cleanup of this contamination could be several hundred million dollars. Significant cost savings could be achieved if airborne methods can serve as a substitute for a portion of ground-based methods.

Many methods have been proposed for the detection and identification of UXO. Surface and airborne measurements of induced EM fields can be used to locate underground objects and structures. Although these methods have typically been used to characterize geologic features, they are also effective in locating man-made objects. While most methods require surface-deployed instrumentation (usually providing greater sensitivity), these methods generally have significantly higher acquisition costs (ranging from $1,000 to $3,000 per acre, depending on site conditions), are extremely time-consuming, and may present risks to personnel, equipment, and the environment. Typically, airborne EM systems have not been used for UXO detection due to limitations in the physics and an inability to position these sensors in close proximity to the targets at or beneath the earth's surface. A recent demonstration of a prototype airborne time-domain EM system by the Oak Ridge National Laboratory (ORNL) led to development of a first generation airborne EM system. In addition to the potential cost savings, an advanced airborne approach will also provide a safer operating environment for personnel performing UXO detection and mapping (stand-off versus direct ground contact); an ability to conduct surveys on difficult terrain or in locations not readily accessible from the surface; a passive, nonintrusive approach by reducing or eliminating disturbance of indigenous plant and animal habitat; an ability to detect non-ferrous ordnance and ordnance-related artifacts; the opportunity to detect ordnance contained in a geologic background containing high ferrous mineral content; and a potential for additional data concerning the anomalies of interest, which may be used for further interrogation and discrimination of ordnance items to aid in safe excavation and remediation.

Airborne EM systems can be deployed in towed-bird configurations, but such deployments cannot support the low altitudes and slow air speeds required for UXO-related applications. For the helicopter surveys employed in this project, a variety of configurations were evaluated including large-loop, small-loop, and double-lobe loop systems.

Altitude, flight path spacing, sample interval along flight lines, background noise, and instrument noise levels determine the minimum target size that can be detected using airborne methods. UXO and UXO-related items at depths of several meters may be detected with airborne EM systems. Surface EM measurements can be used in follow-up surveys to detect smaller objects.

The ORAGS-TEM system is a boom-mounted EM induction system designed for mounting on rigid Kevlar and carbon fiber booms attached to the underside of a Bell 206L Long Ranger helicopter (Figure 1). Rigid booms allow the helicopter to fly closer to the ground, increasing system resolution and permitting precise control of receiver positions, thus allowing more accurate determination of UXO locations. This configuration enabled a nominal instrument altitude of 1 to 3 meters AGL. Survey lines were directly adjacent to one another so that two channels of EM field data were collected for each flight line.

Figure 1. ORAGS-TEM Airborne Electromagnetic System Demonstrated and Evaluated for This Project.

As with most transient EM systems, a current is established in the loop, then rapidly switched off, inducing a secondary magnetic field in the earth, the decay of which is measured in the receiver coils. In the rectangular transmitter configuration, a transmitter cable is wrapped around a 12m x 3m rectangular, composite frame. An alternative lobed configuration wound the transmitter cable in a figure-eight pattern to produce a 3-m x 3-m transmitter loop on either side of the helicopter. The turnoff time for the 12-m x 3-m rectangular transmitter is about 230 μs, and for the lobed configuration about 160 μs. At the BBR two different receiver types were tested: single turn receiver loops having dimensions of about 2.7-m x 2.7-m and smaller loops. The small loop receiver configuration consisted of two 23-cm x 60cm multiple turn loops vertically offset by 34cm. This enabled vertical gradient measurements to be made as well as single loop measurements. The small loop receivers were mounted at the center of a crossbeam connecting the forward and aft booms, providing a distance from the centerline of the helicopter to the receiver center of 4m. A laser altimeter was mounted on the underside of the helicopter, and position information was gathered using differential GPS.

The transmitter, receivers, positioning, and laser altimeter were integrated via a console containing a Pentium-based computer, the transmitter power supply, the transmitter driver board, and a digital system control and acquisition board that governs all system timing and performs digitization for EM receiver coil outputs and auxiliary analog signals. The data from the acquisition board, from GPS positioning, and from altitude and attitude instrumentation are stored on a 60-gigabyte hard drive. These data can be quickly copied to an external drive for transport to a base computer for processing and analysis.

2.2 PROCESS DESCRIPTION

An operational summary is presented here with further detail provided in Sections 3 and 4. Mobilization is conducted by ground transportation of the airborne components, electronic subsystems, and personnel. The helicopter and aircrew are mobilized by air to the base of operations. The base is usually a local or regional airport with suitable security and fuel. The geophysical base station for GPS is established at one or more known civil survey monuments. A processing center is set up at or near the aircraft base of operations.

Installation is conducted by the aircraft mechanic according to Federal Aviation Administration (FAA) requirements and the Supplementary Type Certificate (STC) permit, with support of the ORNL geophysical ground crew. This involves dismounting the tow hook arrangement and installing brackets at these and other hard points in the airframe. The booms, sensors, and recording systems are subsequently attached to the bracket mounts and mounted inside the aircraft.

Survey blocks are chosen and boundary coordinates determined. These are entered into the onboard navigation system. Consideration is given to ambient weather conditions, topography, vegetation, and survey efficiency. After installation, instruments are tested for functionality before and during an initial check flight. Calibration flights are then conducted to determine digital time lags and other parameters required to correct the readings for the actual survey.

After calibration, site surveying commences. The pilot and equipment operator are present in the aircraft during survey operations. The operator is responsible for updating and managing the navigation software as well as real-time quality control (QC) of the incoming geophysical data. Surveying continues on a line-by-line basis until the entire block is covered. Depending on the size of the survey area, multiple flights may be required.

At the end of each flight, data are downloaded to a personal computer (ground station) for QC evaluation. This includes verification of data integrity and quality from all sensor sources. Data from the ground base station instrument for differential GPS are integrated with the airborne data. The dataset is analyzed for completeness of coverage (no large gaps or nonsurveyed areas) and for consistency of survey altitude throughout the survey block. Lines or areas of unacceptable or missing data are noted and resurveyed as appropriate.

Upon completion of the survey, the data are processed to correct for the effects of digital time lag, selective availability in GPS, sensor dropouts, and helicopter rotor noise. EM anomalies are analyzed to derive dig lists and interpretive visual products (e.g., maps) depending on the application.

A variety of skilled personnel are required to conduct this type of geophysical survey. The pilot must be trained in low-level or "ground-effect" flying. The geophysical console operator must be skilled in making real-time decisions regarding data quality in order to conduct immediate re-flights. He must also be intimately familiar with the system in order to diagnose and perform any minor repairs to cabling, electronics, etc. in the field. The processing geophysicist must be familiar with airborne survey operation and data processing, in addition to analysis for UXO targets. All crew must be comfortable with safe operations in and around aircraft.

General and site-specific health and safety plans are generated for each survey project. Following the Department of Energy (DOE) Integrated Safety Management System (ISMS) process, these plans include provisions for general ground safety. This process involved extending the ISMS process using DoD models for UXO site safety, and further extending them to encompass airborne operations as well as wholly new considerations for airborne operations in a UXO theatre. The appropriate management at ORNL, the helicopter operator, and the project sponsor all approve these health and safety plans.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

This technology has evolved from traditional mineral exploration survey systems. While the fundamentals of EM surveying have not changed, the capabilities for mounting extremely high sensitivity EM systems in such an inherently noisy platform were not successfully demonstrated until early 2000. The development of the ORAGS-TEM system involved an evaluation of design options before initiating system construction. This review phase included reanalysis of the results from the 2000 ORAGS-EMP data from BBR, a literature search, an analysis of system configuration options, consideration of flight safety constraints, modeling, ground testing, and review by a peer panel.

Predesign ground testing included acquisition of EM data with a Geonics EM63 around a stationary helicopter, with and without the engine running, in order to map the noise field in the vicinity of the helicopter. As a result of the review phase, design attributes were selected for the demonstration system. A time-domain architecture was chosen as the primary focus, with the intent of developing a system that could also acquire data to assess probable frequency-domain performance. Transmitter structure and electronics, transmitter waveform, receiver configuration and electronics, and interfaces with other instruments that provide positioning data were selected. Initial ground-testing was done at a convenient outdoor location to test sensitivity to UXO-like items in anticipation of subsequent measurements in the presence of a helicopter.

Three shakedown tests were performed with ORAGS-TEM prototypes before the 2002 BBR test. These shakedown tests were conducted near Toronto, Ontario, in December 2001; near Hyannis, Massachusetts, in March 2002; and near Albuquerque, New Mexico, in May 2002. Several incremental improvements were made to the system during the course of these tests.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Airborne surveys for UXO are capable of providing data for characterizing potential UXO contamination at a site at considerably lower cost than ground-based systems. Current indications are that the ORAGS-Arrowhead magnetic survey cost may approach $60 per acre under *optimal* conditions. An optimized EM system under favorable conditions will still require interleaving, and therefore will have higher cost, most likely about $100 per acre based on production efficiency relative to ORAGS-Arrowhead under similarly optimal conditions. Under more typical conditions, the cost will probably approach $200 per acre (see Table 8 for breakdown). Airborne systems are particularly effective for sites characterized by low-growth vegetation and minimal topographic relief. They can also be used where heavy brush, mud, or swampy conditions make it difficult to conduct ground-based surveys.

The performance of the airborne EM system compares favorably with that of airborne magnetometer systems at the same test site. Small targets (e.g., 60mm mortars) have weak but detectable responses with both systems when data are acquired at 1-2m AGL. Performance under field conditions, particularly at less pristine sites than the BBR test site, will clearly fall short of the performance at the BBR test site, but there are no data available to provide a quantitative assessment due to the limited scope of this test. Performance is clearly lower than that of ground surveys (e.g., towed array surveys using Multi-Sensor Towed Array Detection System [MTADS]), which can operate with sensors at less than 0.5m AGL.

Both airborne and ground magnetometer systems are susceptible to interference from magnetic rocks and magnetic soils. Airborne EM systems are less vulnerable to these natural conditions, as proven by numerous ground-based surveys. Rough topography and tall vegetation limits the utility of helicopter systems, necessitating survey heights too high to be of practical benefit.

At the time of this demonstration, no competing technologies to the ORAGS-TEM were known to exist for airborne EM surveys.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

Although airborne methods have historically been used to characterize geologic features, recent technological developments have led to an increase in sensitivity that makes these methods reasonable choices for detecting many types of UXO. The analysis of EM data for the project site focused on identifying the locations of surface and near-surface UXO (and ordnance debris) and distinguishing between anomalies that occurred due to natural processes and those that have resulted from human activity. Under the direction and guidance of the U.S. Army Engineering and Support Center, Huntsville (USAESCH), ORNL and its team members acquired high-resolution EM data in support of the identification and mapping of surface and near-surface UXO and ordnance debris within the areas of interest at BBR. This data acquisition platform and mission flights were characterized by innovative technical criteria, including an extremely low flight altitude and higher data acquisition rates. GPS and altitude information were also acquired. The following summary describes the sensor platform, performance parameters, and the utility of the data for identifying UXO and ordnance debris.

The system was designed for the detection of small amounts of man-made metal (potentially as small as 5 kg to 10 kg), but also to respond to larger, man-made metallic objects. Simultaneously, differential global positioning system (DGPS) data were acquired to geo-locate the EM data. The EM system was mounted on a Bell 206L Long Ranger helicopter and flown at 1m to 3 AGL. Flight line spacing ranged from 1m to 10m (depending on receiver coil configuration) with an aircraft speed of approximately 10m to 14m/s.

As discussed previously, the objectives of this project centered on demonstrating the usefulness of the technology as a tool to aid in footprint reduction and to help delineate areas of concern for ordnance contamination. Expected detection of individual ordnance items included M38 practice bombs and 2.25-in and 2.75-in aerial gunnery rockets, as well as the actual locations and boundaries of aerial bombardment targets. Additional performance objectives for this project are listed in Table 1.

3.2 SELECTION OF TEST SITES

The former BBR, also known as the Pine Ridge Gunnery Range, is a FUDS located within the Pine Ridge Indian Reservation in Shannon and Jackson counties, South Dakota. Totaling more than 339,000 acres, portions of the site are flat and devoted to farming and ranching. The remaining acreage is badlands that are gently rolling to nearly vertical in topographic relief that have been formed due to the extensive rapid erosion of the soft, fine-grained underlying sediments. The badlands are primarily devoted to grazing. A portion of the site is now part of the Badlands National Park.

Table 1. Performance Objectives of ORAGS-TEM Airborne Electromagnetic System.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Qualitative	ORAGS-TEM system aerodynamically stable	Pilot report	Yes
Qualitative/Quantitative	ORAGS-TEM data can be used for discrimination	Processing of selected data sets shows different response from some types of UXO and scrap.	Yes. Time constant analysis of test site data indicates that a level of discrimination may be achievable. (Ref: ESTCP Project 200101 Final Report, August 2004; Holladay et al, 2004a, 2004b.)
Quantitative	Reduced system noise levels	Comparison to previous noise levels	Yes
Quantitative	Improved sensitivity	Comparison to previous detection thresholds over calibrated test grid	Yes
Quantitative	Minimize coupling to active helicopter noise source	Compare noise levels from various orientations of EM receiver	Yes

With regard to historical ordnance, numerous areas exist across the entire site that were used for aerial gunnery, aerial bombardment, and surface-based gunnery activity. Historical records indicate that use of the range began in the early 1940s and terminated in the mid-1970s. Groups that used the range include Rapid City Air Force Base (AFB) (now Ellsworth AFB), the U.S. Army, and the South Dakota Army National Guard. Ordnance types found at the former BBR include 75mm high explosive (HE) projectiles; 105mm and 155mm HE and illumination projectiles; 8-in HE projectiles; M38 practice bombs; M50 and M54 incendiary bombs; and 2.75-in and 2.25-in rockets.

Two specific sites were selected for data acquisition for this evaluation project: The ORNL-established airborne system Calibration Site, and Bombing Target 1, both on Cuny Table. These sites were chosen to enable, where possible, direct comparison of results from the new generation airborne systems with results of previous airborne and ground-based geophysical systems for UXO detection and mapping. These include airborne surveys with the Aerodat HM-3 system, the ORAGS-Hammerhead system, the ORAGS-EMP system, the ORAGS-Arrowhead system, and the ORAGS-VG system, and ground-based surveys at the Calibration Site with a Geometrics G-858 magnetometer system and a Geonics EM61 induction TEM system.

Additional reasons these sites were chosen included favorable terrain, benign underlying geology, and reasonable ordnance objectives (size, expected depth, composition, etc.). All these factors contributed to an increased likelihood of project success.

3.3 TEST SITE HISTORY AND CHARACTERISTICS

3.3.1 BBR Calibration Test Site

In 1999 and 2000, ORNL and USAESCH established a test grid at BBR to support evaluation of airborne magnetometer systems. The test grid was constructed in an area of relatively flat rangeland on Cuny Table, a mesa bounded by steep escarpments bordering Badlands National Park. The soil is unconsolidated and thick, consisting mainly of layers of sand and silt. The geological background of the site is thus relatively clean, producing few sizeable short wavelength EM anomalies.

Ordnance and nonordnance items were buried at a total of 53 different locations, distributed along eight rows spaced 15m apart, in a 4-acre area, about 150m x 105m. Buried items were as small as 8-in nails and as large as an inert 250-lb bomb. Along the rows, many items are evenly spaced 20m apart, but some items are as close as 10m and as far apart as 75m. This is shown schematically in Figure 2. The accuracy of the locations of the buried items is generally good but varies because the items were not all buried at the same time and varying quality GPS systems were used to determine their locations. Airborne systems that have acquired data at the BBR test grid at one time or another include the HM-3, ORAGS-Hammerhead, ORAGS-EMP, ORAGS-Arrowhead, and ORAGS-TEM systems.

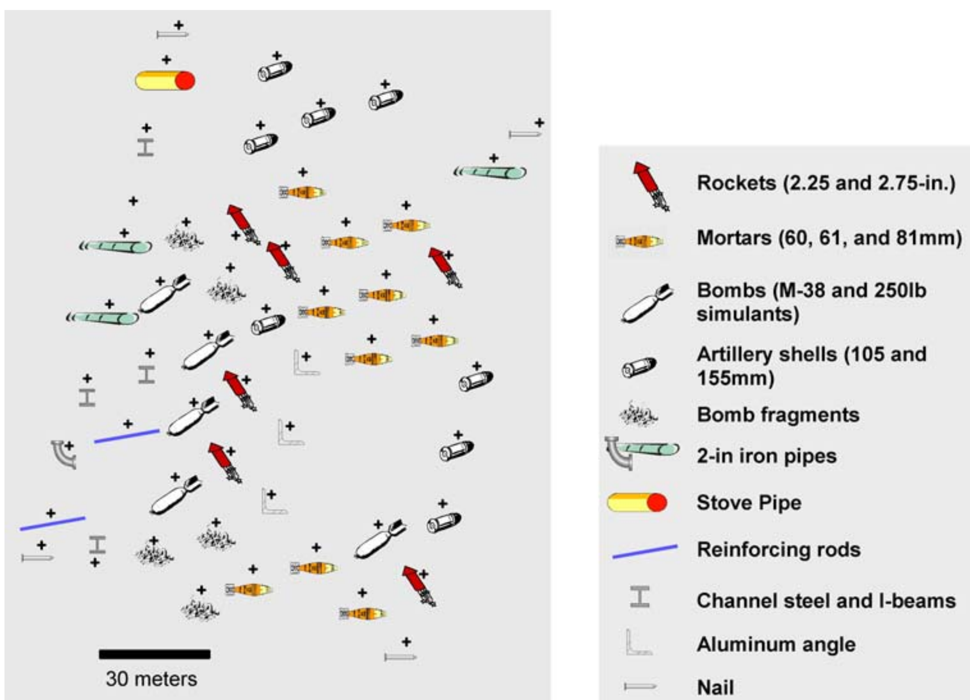

Figure 2. Schematic Map of BBR Test Site.

3.3.2 Bombing Target 1

Bombing Target 1 (see Figure 3) was used for training missions in World War II. As a result, most ordnance at the site are M-38 100-lb, sand-filled practice bombs. These contain approximately 10-15 kg of steel, but much smaller fragments are also found at the site as well as smaller ordnance items. The target is marked with a circular berm and crosshairs (Figure 3) 1.0-1.5 m in height. A barbed wire fence passes through the center of the target with an east-west orientation. Some of the ordnance items have been removed from the northern side of the fence during evaluation of previous mapping projects. To our knowledge, the area south of the fence has not been excavated for UXO, although it is part of a field and is routinely plowed. The site was previously surveyed with the Naval Research Laboratory (NRL) MTADS system in 1997 (McDonald et al, 1998), and subsequently by the ORNL with the HM-3 magnetometer-based system in 1999. Some excavation of UXO was conducted for validation of the 1997 MTADS survey in the area north of the fence (Andrews et al, 2001). In the same 2002 deployment described in this report, we acquired data over Bombing Target 1 with the ORAGS-VG Vertical Gradient system. These results will be discussed in a separate report to ESTCP.

Figure 3. Bombing Target 1 at BBR.

3.4 PHYSICAL CONFIGURATION AND OPERATION

Bombing Target 1 at BBR had been previously surveyed by the NRL MTADS magnetometer array (McDonald et al, 1998) under the guidance of the ESTCP Program Office. Selected anomalies were excavated as part of the analysis of those data before the data described in this report were acquired. The site was subsequently surveyed with the HM-3 system in 1999. From the two data sets (MTADS and HM-3), 146 items were excavated north of the fence at Bombing Target 1, including 17 targets selected from the airborne data. These results were assessed by Andrews et al, 2001. It is possible that surficial objects have moved by frost-heaving or domestic animals between the earlier surveys and the 2002 ORAGS-Arrowhead survey and that buried objects south of the fence have been moved due to plowing, but these effects are assumed to have a minimal impact.

3.5 PREDEMONSTRATION TESTING AND ANALYSIS

In addition to the shakedown tests described in Section 2.3, adjustments were made to the console between the completion of the third shakedown test (New Mexico) and the initiation of data acquisition for the BBR Demonstration. These included improvements to the transmitter to reduce early time jitter (to enable acquisition at earlier decay times) and testing of vibration mounts.

3.6 TESTING AND EVALUATION PLAN

3.6.1 Demonstration Setup and Start-Up

Mobilization involved transporting all system components by trailer to Rapid City and installing them on a Bell 206L Long Ranger helicopter. All system components, including the transmitter/ data recording console, GPS receivers, and laser altimeter were tested to ensure proper operation and performance. The Mission Plan was read and signed by all project participants to assure safe operation of all systems.

3.6.2 Period of Operation

Mobilization of the geophysical crew from Oak Ridge, and the flight crew from Toronto, began on September 8, 2002. This required two and a half days travel to Rapid City with the geophysical equipment trailer. The helicopter crew departed Toronto on September 9, and both the geophysical crew and the helicopter crew arrived on September 10. The project involved acquisition of both magnetometer and EM data. Initial measurements were made with the EM system September 14-16. Repairs to the helicopter and the attitude measurement unit resulted in a delay in acquisition of EM data until September 25. EM acquisition was completed on September 28. Magnetic data acquisition was initiated after acquisition of EM data was complete and ended on October 7. De-installation was completed on October 8, and the geophysical and air crews departed for another project in Arizona.

3.6.3 Areas Characterized

Two sites were surveyed, as described previously. Several configurations of the system were tested at the BBR test site. At Bombing Target 1, approximately 14 hectares were surveyed with the large-loop receiver configuration, and a smaller area, approximately 2.4 hectares, was covered with a small coil system.

3.6.4 Residuals Handling

This section does not apply to this project.

3.6.5 Operating Parameters for the Technology

The ORAGS -TEM system is designed for daylight operations only. Lines were flown in a generally north-south pattern. Data were sampled at a rate of 10.8 kHz. Survey speeds at the BBR sites ranged from 10-14 m/s. These speeds were required to minimize positional errors with a two-receiver system. Higher speeds, perhaps 30 m/s or 100 km/hr, are anticipated with a production system where a wider swath will allow coarser line spacing. Survey altitude of 1-3 m AGL was safely achievable. Data were acquired at higher altitudes at the test site to guide performance assessments. Line spacing was dependent on the receiving coils used and the altitude of the test. In general, data were acquired in a "vertical difference" configuration with one coil mounted above the other. With small receiver coils at 1.0-1.5m altitude AGL, a line spacing of 1m was used. Large loop receivers at this altitude required 3m line spacing. Large loop data acquired at Bombing Target 1 did not use a vertical difference configuration but operated with one large loop coil on each side of the aircraft to maximize efficiency in two-channel production mode.

3.6.6 Experimental Design

Data were acquired to compare several system parameters. The system parameters were selected on the basis of previous shakedown tests, but it was determined that some parameters could not be adequately assessed without acquiring data over a documented test site where only one parameter was changed at a time. The parameters that were assessed at BBR through data acquisition at the test site were:

1. *Flight performance*. Previous shakedowns had shown in-flight sensitivity associated with the mass distribution of the system. We reduced overall mass by replacing a copper transmitter cable with an aluminum transmitter cable and by replacing plywood crossbeams with fiberglass tubes. These improvements could only be assessed by flight-testing.

2. *Large/small loop receiving coils.* Previous shakedown tests had shown mixed results with coils that were either small (30cm x 50cm multiturn) or large (single turn 3m x 3m). We acquired data with both configurations. The large loop receiver coil configuration is shown in Figure 4 and the small loop receiver coil configuration in Figure 5.

3. *"Vertical difference" configurations (subtract upper loop response from a lower loop response with ~30 cm separation)* versus *vertical field (single loop) configurations.* These data were acquired simultaneously with data from the single receiving coils by recording from upper and lower loops separately. Gradient coils for the small loop system are positioned at the top and bottom of the frames shown in Figure 5, and for the large loop system are at the top and bottom of the boom tubes in Figure 4.

4. *Transmitter configuration comparison.* We had previously acquired data with two different transmitter configurations—a simple rectangular loop that measured 3 m x 12 m and a lobed transmitter in which the central portion of the transmitter was eliminated to reduce induction in the helicopter, and thus reduced noise. A photograph showing the black transmitter cable on the boom tubes with a lobed configuration is shown in Figure 6. The lobed configuration was deployed in two formats—symmetric and anti-symmetric current directions in the transmitter lobes.

Figure 4. ORAGS-TEM Large Receiver Loop Configuration.
(Single loops of wire are attached to the top and bottom of the 3m x 3m outer portion of the booms to form the large-loop gradient receiver.)

Figure 5. ORAGS-EM Small Loop Receiver Coil Configuration.
(Inset shows enlarged view of coils.)

5. *Base frequency tests.* Although we had compared base frequency tests in previous shakedowns, modifications to the weight distribution (see item 1 above) would affect vibrational harmonics of the system, and fine tuning of the system console would allow testing of higher base frequencies than in previous shakedown tests.

6. *Vibration-isolated mounts.* Previous tests had been conducted with receiver coils mounted rigidly to the support structure. Most major noise sources had been identified and eliminated prior to the BBR deployment, so a test with the small coil receivers coupled to the support structure through isolation mounts was called for to assess the potential for further reduction of vibration induced noise.

Figure 6. Lobed 3 m x 3 m Transmitter Configuration.
(Note the transmitter cable does not extend across a portion of the front boom.)

Data quality objectives (DQO) to be used for this technology demonstration focused on prior generation airborne results as the baseline performance condition as well as previous MTADS demonstration data.

Given the various considerations associated with both the interpretation of airborne geophysical survey data and the calculations of the various performance parameters, DQO for the demonstration of the ORAGS-TEM system should be expected to meet or exceed the current performance parameters.

3.6.6.1 Quality Control

All data were examined in the field to ensure sufficient data quality for final processing. Each of the items discussed in the previous sections were considered and tested. During survey operations, flight lines were plotted to verify full coverage of the area. Missing lines or areas where data were not captured were reacquired. Data were also examined for high noise levels, data dropouts, or other unacceptable conditions. Lines flown, but deemed to be unacceptable for quality reasons, were reflown.

3.6.6.2 Positioning

During flight, the pilot was guided by an onboard navigation system that used real-time satellite-based DGPS positions. This provided sufficient accuracy for data collection (approximately 1m), but was inadequate for final data positioning. To increase the accuracy of the final data positioning, a GPS base station, CT-1 on Cuny Table near the field sites, was used. This site was established in 1999 during ongoing engineering evaluation/cost assessment (EE/CA) investigations by Parsons Engineering Science. Its location is WGS-84 43.5204408, 102.6983032, 3307.86m.

Raw data in the aircraft and on the ground were collected. Differential corrections were post-processed to provide approximately 20-cm accuracy for the airborne GPS antenna in the final data positioning, as specified by the manufacturer. Additional positioning errors will be introduced by any pitch, roll, or yaw of the aircraft. The final latitude and longitude data were projected onto an orthogonal grid using the North American Datum 1983 (NAD 83) South Dakota CS 83 South Zone. Vertical positioning was monitored by laser altimeter with an accuracy of 2cm, with increased sensor altitude errors due to topography and aircraft roll. No filtering was required of these data although occasional dropouts were removed.

3.6.6.3 Electromagnetic Data Processing

The EM data were subjected to several stages of geophysical processing. The processing flow has not been finalized to the extent that it has in the ORAGS total magnetic field system, but follows some of the same steps.

The 10,800 Hz raw data were desampled in the signal processing stage to a 120 Hz recording rate. All other raw data were recorded at a 60 Hz sample rate. Data were converted to an ASCII format and drift corrected.

After drift correction was completed, the modified ASCII data were imported into a Geosoft format database for processing. With the exception of the differential GPS postprocessing, all further data processing was conducted using the Geosoft software suite and proprietary ORNL algorithms and filters. The QC, positioning, and EM magnetic data processing procedures (steps 1-3) are described below:

1. Data were inspected according to the QC procedure described in Section 3.6.6.1.

2. Sensor positions were corrected according to the procedure described in Section 3.6.6.2.

3. Filtering/Differencing
   Other filters, usually high- or low-pass filters, were applied as needed to individual channels we chose to focus on. For vertical gradient measurements, we differenced the upper and lower receivers for each channel.

Data were rarely broken up from flights to individual lines as gridding and analysis could as easily be done on full flights of data.

3.6.7 Sampling Plan

This section does not apply to this report.

3.6.8 Demobilization

EM acquisition was completed on September 28. Magnetic data acquisition using the ORAGS-Arrowhead system was initiated after acquisition of EM data and ended on October 7. De-installation and demobilization were completed on October 8.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

Evaluation effectiveness was determined directly from comparisons of the processed/analyzed results from the demonstration survey and the results of previous airborne and ground-based surveys. These comparisons include both the quantitative and qualitative items described here. Demonstration success was determined as the successful acquisition of airborne geophysical data (without any aviation incident or airborne system failure) and meeting the baseline requirements for system performance as established in Section 3.1. Methods utilized by ORNL on both current and past airborne acquisitions to ensure airborne survey success include daily quality assurance (QA)/QC checks on all system parameters (GPS, transmitter operation, data recording, system compensation measurements, etc.) in the acquired data sets, continual inspections of all system hardware and software ensuring optimal performance during the data acquisition phase, and review of data on completion of each processing phase.

Several factors associated with data acquisition cannot be strictly controlled, such as aircraft altitude and attitude. Altitude is recorded and enters into the data analysis and comparisons with previous results. The aircraft attitude measuring system provides a documented database that cannot be directly compared with previous surveys when this system was not available. Consistent and scientific evaluation of performance is achieved by using identical or parallel (where parameters are dataset dependent) processing methods with identical software to produce a final map, and following consistent procedures in interpretation when comparing new and existing datasets from the test sites.

Data processing involves several steps, as described in Section 3.6.6.3. Each step will be performed in the same manner on data acquired with sequential generations of the system at the same sites to provide a basis for comparing the performance of the systems. The processing procedures have been selected and developed from experience with similar data over a span of more than 5 years for optimal sensitivity to UXO.

DQO, as described in Section 3.6.6, Experimental Design, was used for this demonstration. Surveys over the previously described test areas are conducted as described in Section 3.6. Data were acquired with a variety of configurations and at a variety of flight altitudes over the test areas and configurations, as described in Section 3.6.6. Data confirmation is in accordance with the processes previously described in this section.

Table 2 identifies the expected performance criteria for this evaluation, complete with post-demonstration performance results (quantitative) and/or definitions and descriptions (qualitative).

Table 2. Performance Criteria for This Demonstration.

Performance Criteria	Expected Performance Metric (Pre-Demo)	Performance Confirmation Method	Observed Performance (Post-Demo)
Primary Criteria (Performance Objectives) – Quantitative			
System Performance	Detection threshold (sensitivity) Anomaly positional accuracy	Comparison to prior collected ground-based geophysical data	SNR assessments show similar performance (e.g., project Final Report, ORNL, 2004)
Primary Criteria (Performance Objectives) – Qualitative			
Process Waste	None	None	None
Factors Affecting Technology Performance	Helicopter geophysical noise GPS satellite constellations Cultural artifacts	Comparison to expected noise levels based on prior geophysical measurements around the helicopter Record constellation changes and use during positioning accuracy determination Compare fence line and post anomalies at Bombing Target 1 against previous survey results	Noise similar to previous surveys Recorded ORAGS-TEM shows two peaks at fence, where magnetic data have one peak
Reliability	False positives (FP) – less than or equal to 6%	Comparison to prior collected ground-based data and excavations (as needed)	No estimate of FPs[1]
Secondary Criteria (Performance Objectives) – Quantitative			
Hazardous Materials	None expected, other than spotting charges in M-38 practice ordnance	Observations and documentation during excavations	No hazardous materials encountered
Secondary Criteria (Performance Objectives) – Qualitative			
Reliability	No system or component failures	Observations and documentation	Some transmitter overheating if current too high.
Ease of Use	Pilot "comfort" when flying with the system installed No ballast required	Observations and documentation Observations and documentation	The pilot reported no issues with maneuverability, and similar positive performance when compared to the ORAGS-Arrowhead magnetic system. No ballast required.
Safety	Conformance with all FAA requirements and requirements as documented in the Mission Plan	Observations and documentation	System met all FAA requirements

Table 2. Performance Criteria for this Demonstration. (continued)

Performance Criteria	Expected Performance Metric (Pre-Demo)	Performance Confirmation Method	Observed Performance (Post-Demo)
Versatility	Cultural feature detection and mapping	Comparison of anomaly count, strength, and position to previously collected data at Bombing Target 1 regarding barbwire fence crossing the middle of the targets	Cultural features clearly distinguished from ordnance
Maintenance	System mount points, hardware, and component inspection	Observations and documentation	Minimal wear and tear
Scale-Up Constraints	None	Observations and documentation	Test site data provide guidance on positioning and spacing of additional receiving coils.

[1] Validation, i.e. assessment of ordnance detection and FPs, could not be done because no postsurvey excavation was conducted.

4.2 PERFORMANCE CONFIRMATION METHODS

Estimation of two of the system performance criteria was to be based on comparisons of system performance at the BBR Test Site and qualitative analysis of data acquired at Bombing Target 1. Validation, i.e. assessment of ordnance detection and FPs, could not be done because no postsurvey excavation was conducted.

4.3 DATA ANALYSIS, INTERPRETATION, AND EVALUATION

The ORAGS-TEM data does not in itself distinguish the numerous features mapped as UXO or ferrous scrap without interpretation. The maps provided in this report depict bombing targets (areas of high ordnance density), infrastructure (larger items or areas of ferrous debris associated with human activity), and potential UXO items (discrete sources). Those responses, interpreted as potential UXO, will likely also include smaller pieces of ferrous debris.

The BBR Calibration Test Site, described in Sections 3.2 and 3.3, was established to verify the system response to expected UXO items under local geologic conditions. Before and after seeding target items in 1999 (other than the iron stakes), the area was surveyed with a Geometrics G858 magnetic gradiometer and real-time DGPS navigation system. Before testing in 2000, areas north and east of the original test site were magnetically surveyed, then seeded with additional ordnance items. After seeding, it was surveyed with the G858 magnetometer and an EM61 ground-based EM system.

The preseeding results showed occasional anomalies associated with ferrous objects or magnetic soils. Every attempt was made to place targets at a sufficient distance from these anomalies to create a distinct anomaly. Illustrations of seeded items are provided in Figure 2.

4.3.1 Results from BBR Test Site

4.3.1.1 <u>Comparison of Gridded Data at the BBR Test Site</u>

Figures 7 through 13 show maps derived from data acquired during the 2002 test and previous tests at the BBR test site. With the exception of the ground-based measurements in Figures 9 and 12, all data were acquired at a nominal altitude of 1.0-1.5m AGL at an average air speed of 12 m/s. These are lower speeds than commonly used in airborne magnetometer surveys and are required in order to maintain adequate positional control for the two-receiver system. A TEM system with more channels could be flown at velocities approximately equal to those of the magnetometer system. The results from previous tests are provided to allow comparison of the new prototypes with ground-based EM61 data, the earlier ORAGS-EMP airborne prototype, ground-based magnetometer data, and ORAGS-Hammerhead airborne magnetometer data. Figure 2 represents the columns and rows of the Calibration Site and provides the key to understanding the results represented in Figures 7 through 13. Two receiving channels were available for the current system, and these were generally placed on one side of the aircraft, leaving the other side with ballast to maintain aircraft stability. Two base frequencies were selected for these tests, 90 Hz and 270 Hz. The 90 Hz base frequency allowed more of the decay to be recorded, thus opening the door for advanced processing aimed at discrimination. The 270-Hz base frequency had slightly better SNR over most targets because of more signal stacking. The ORAGS-TEM results are for 270-Hz base frequency except where noted. The entire rectangle was used as a transmitter for most tests, except for one test series when a lobed transmitter was tested.

In general terms, the "swath" of an EM sensor may be defined as the zone at the ground surface that is illuminated by the transmitter and scanned by its multiple-receiver array. In the context of the two-channel ORAGS-TEM system evaluated by this project and for the purposes of this report, the term "footprint" will be used as an abbreviation for the "receiver footprint," defined as the diameter of the region on the ground beneath the receiving coil within which a typical target can be detected. It is assumed that the transmitted field is approximately uniform on the ground in the vicinity of the receivers, which is valid when the vertical distance between the ground surface and the transmitter plane is less than the smallest horizontal dimension of the transmitter.

At low altitudes, the small coils have a footprint of about 1.5 m. For flights at approximately 1m laser altitude at the BBR test site, small coil data were acquired along three lines at 1m nominal separation for each row of targets. Additional lines were flown midway between each row of targets. Full coverage was not practical with a single small receiving coil, but will be appropriate for a final production system, which will have more receiving coils.

Figure 7 shows data acquired at the test site with the small vibration-isolated coil configuration. The small receiving coils were placed above and below the boom tubes to allow direct comparison of vertical component and "vertical gradient" results. Only the response from the first time sample ending at 93 μs is plotted in Figure 7.

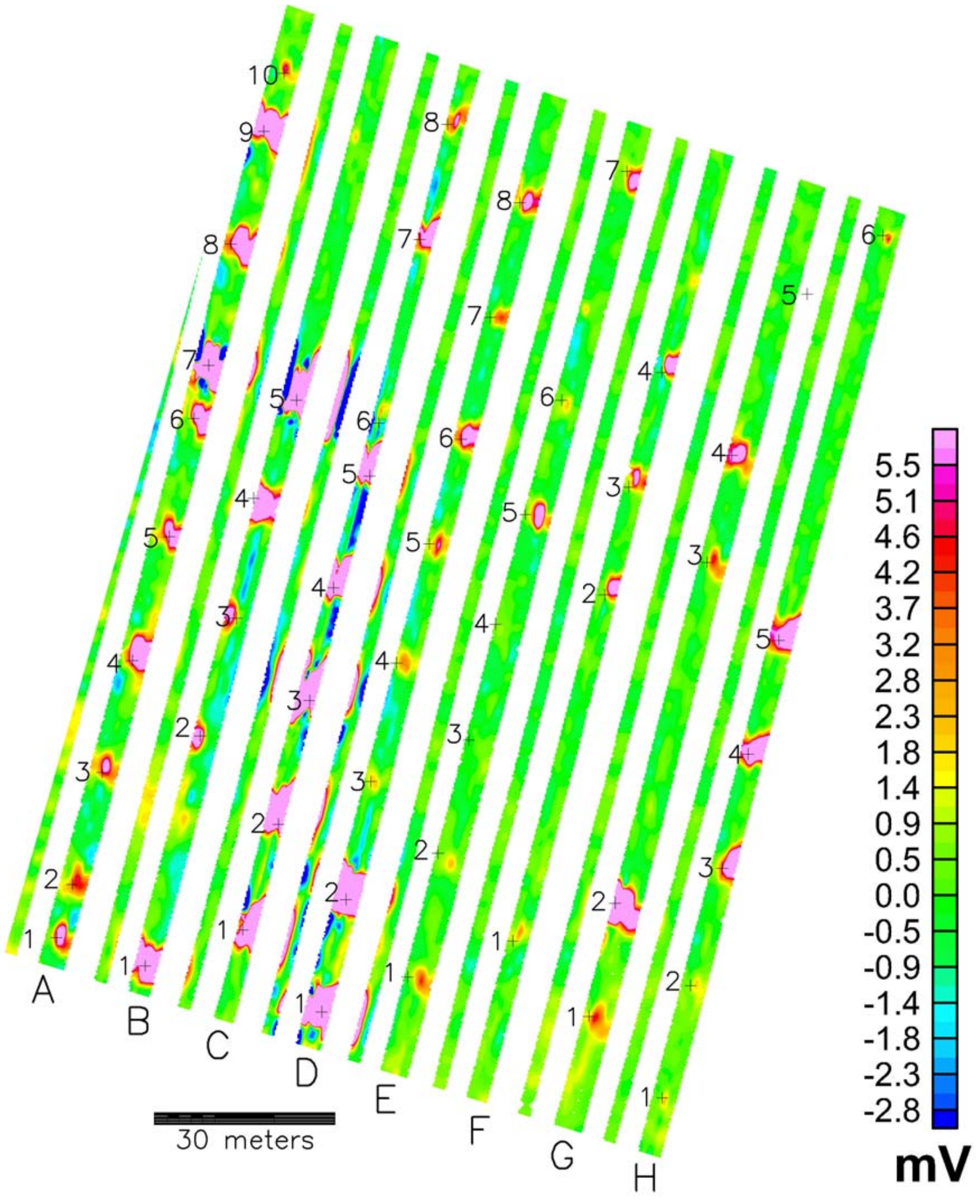

Figure 7. ORAGS-TEM Results from BBR Test Grid, Vibration-Isolated Lower Small Loop Receiver. (Data acquired at 270 Hz base frequency and 1.0-1.5m altitude.)

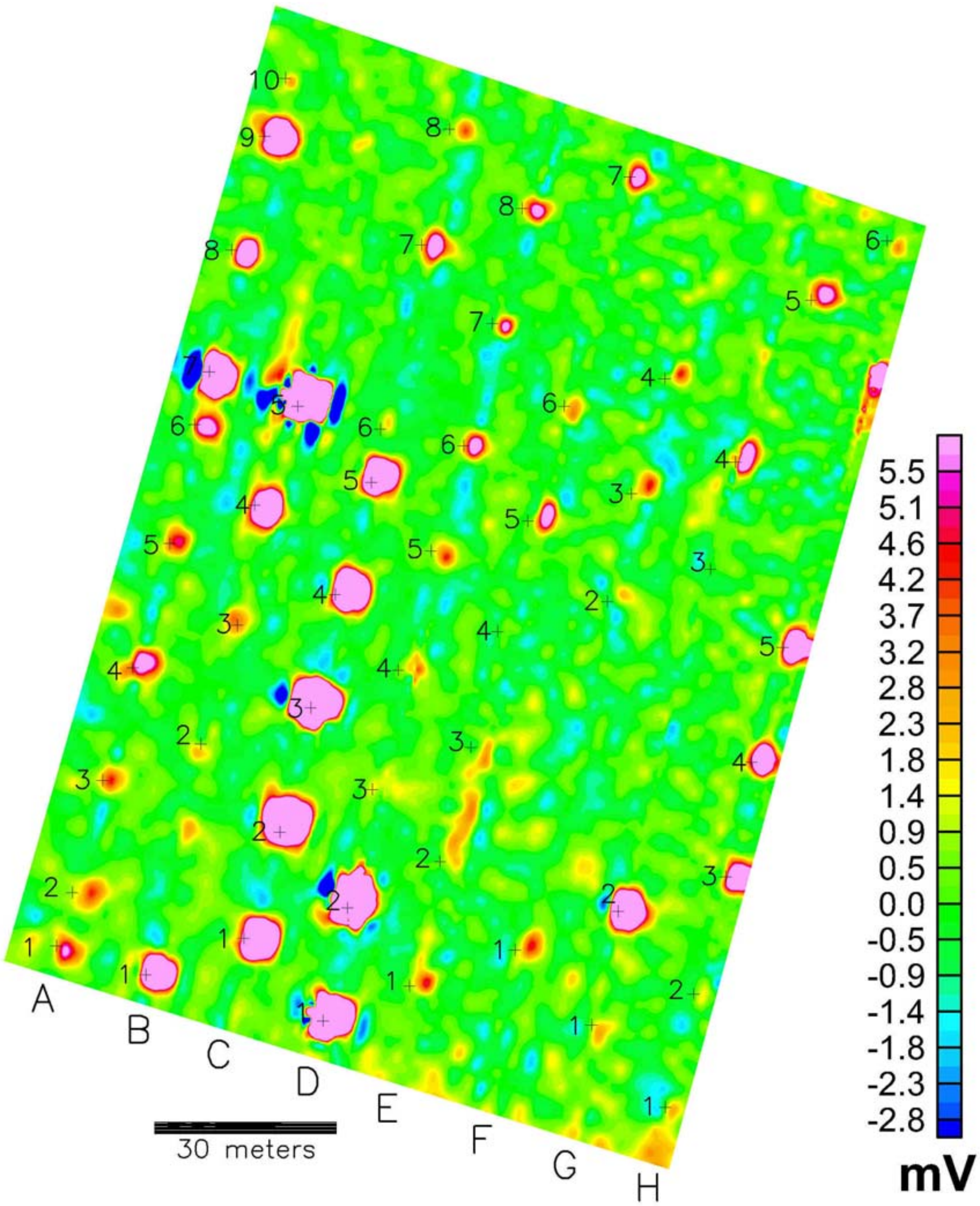

Figure 8. Results from ORAGS-TEM, BBR Test Grid, Lower Large Loop Receiver.
(Data acquired at 270-Hz base frequency and 1.0-1.5m altitude.)

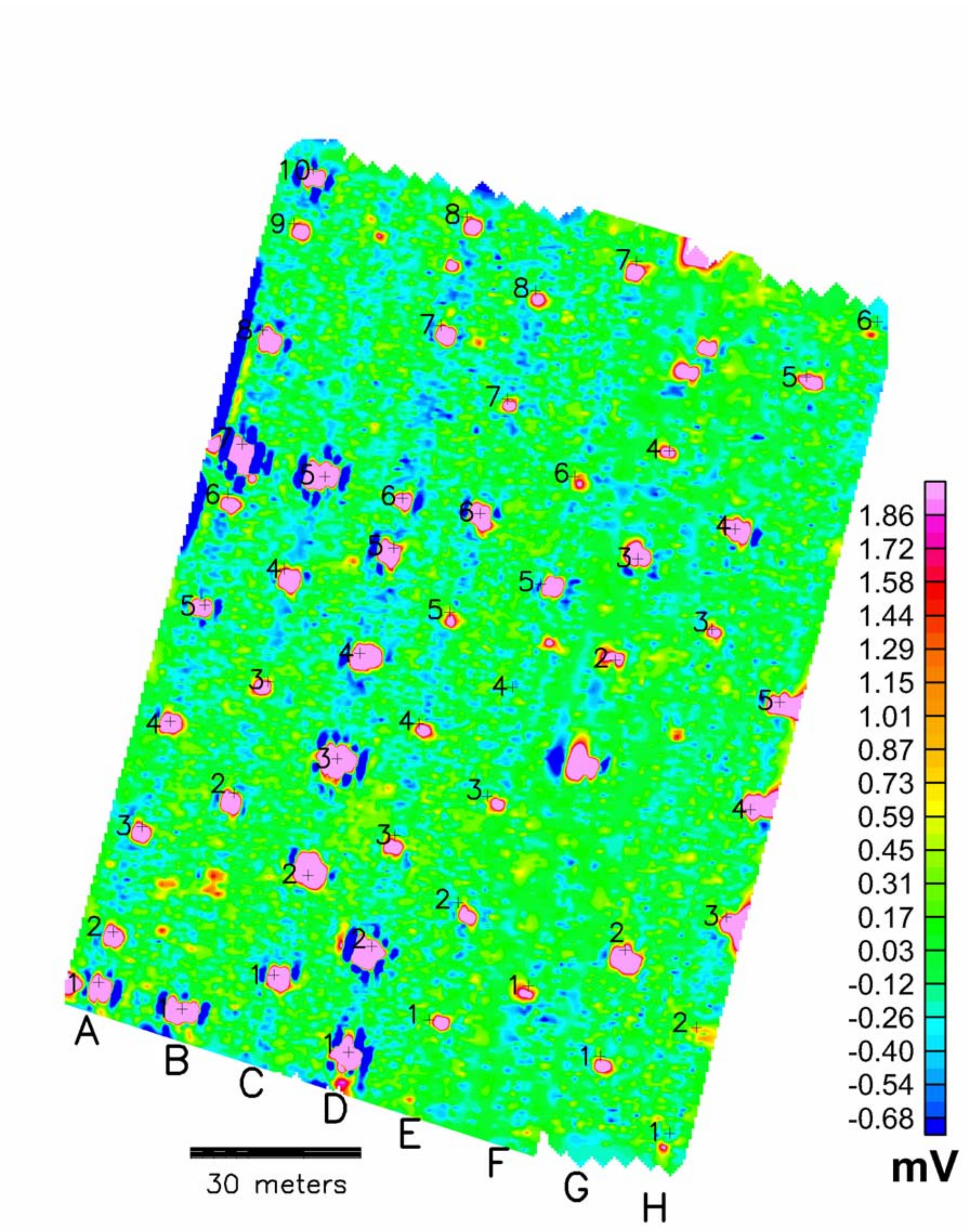

Figure 9. Results from Ground-Based EM61, Bottom Coil, BBR Test Grid, for Comparison with Airborne Results.

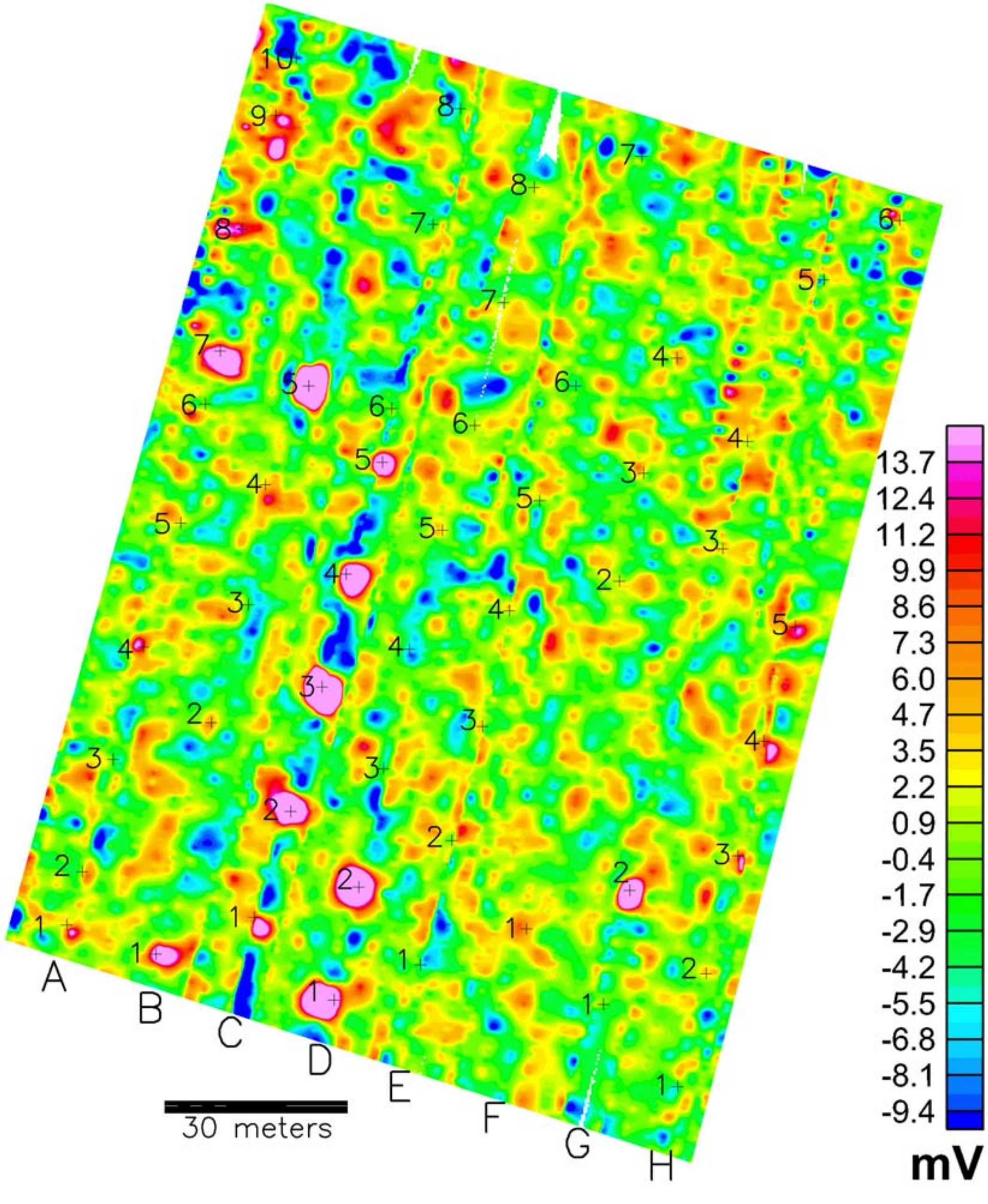

Figure 10. Results from EM-61AB-Based Airborne Proof-of-Concept System, BBR Test Grid, Outer Coil Receiver.

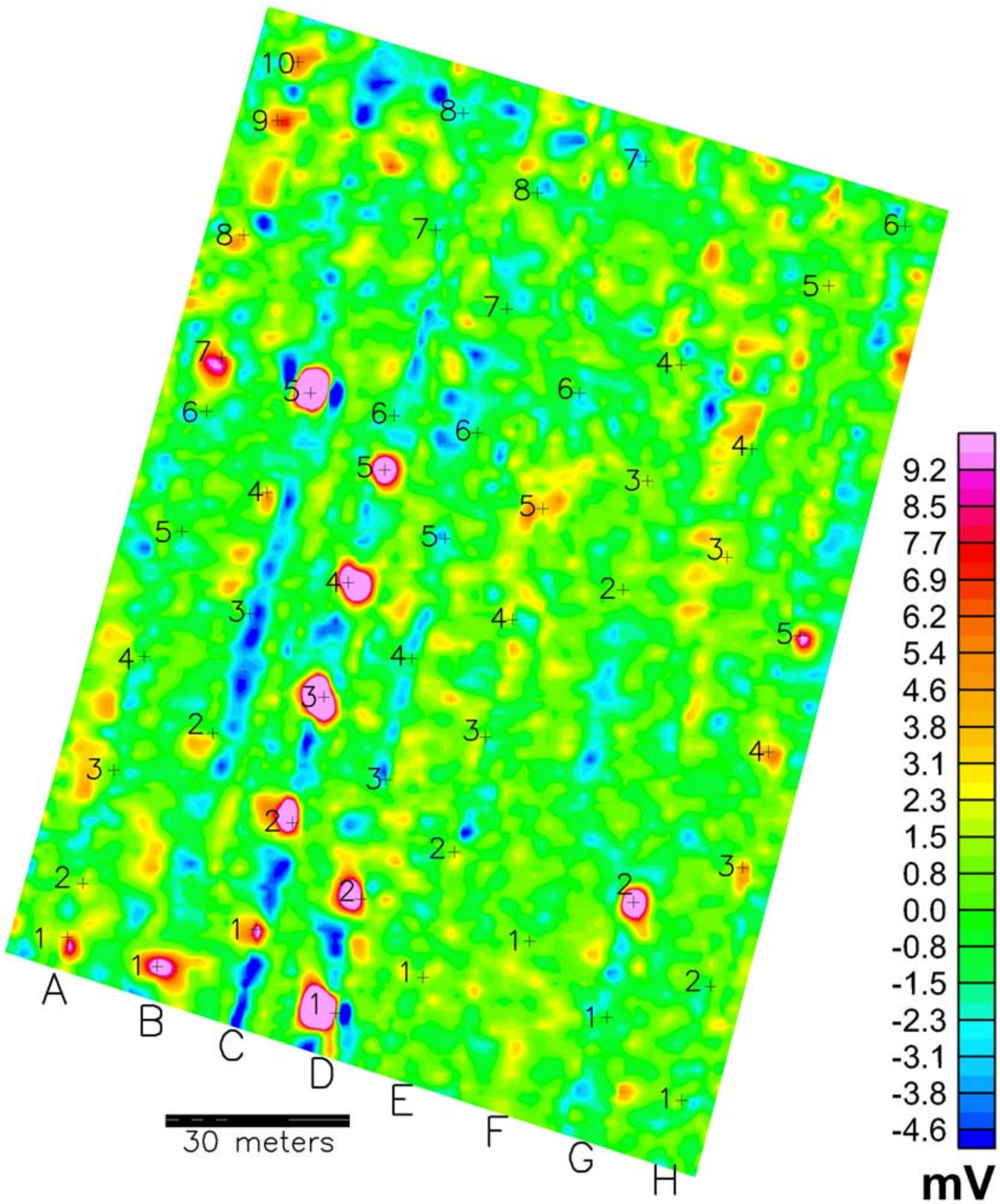

Figure 11. Results from EM-61AB-Based Airborne Proof-of-Concept System, BBR Test Grid, Horizontal Difference (outer coil minus scaled inner coil)**.**

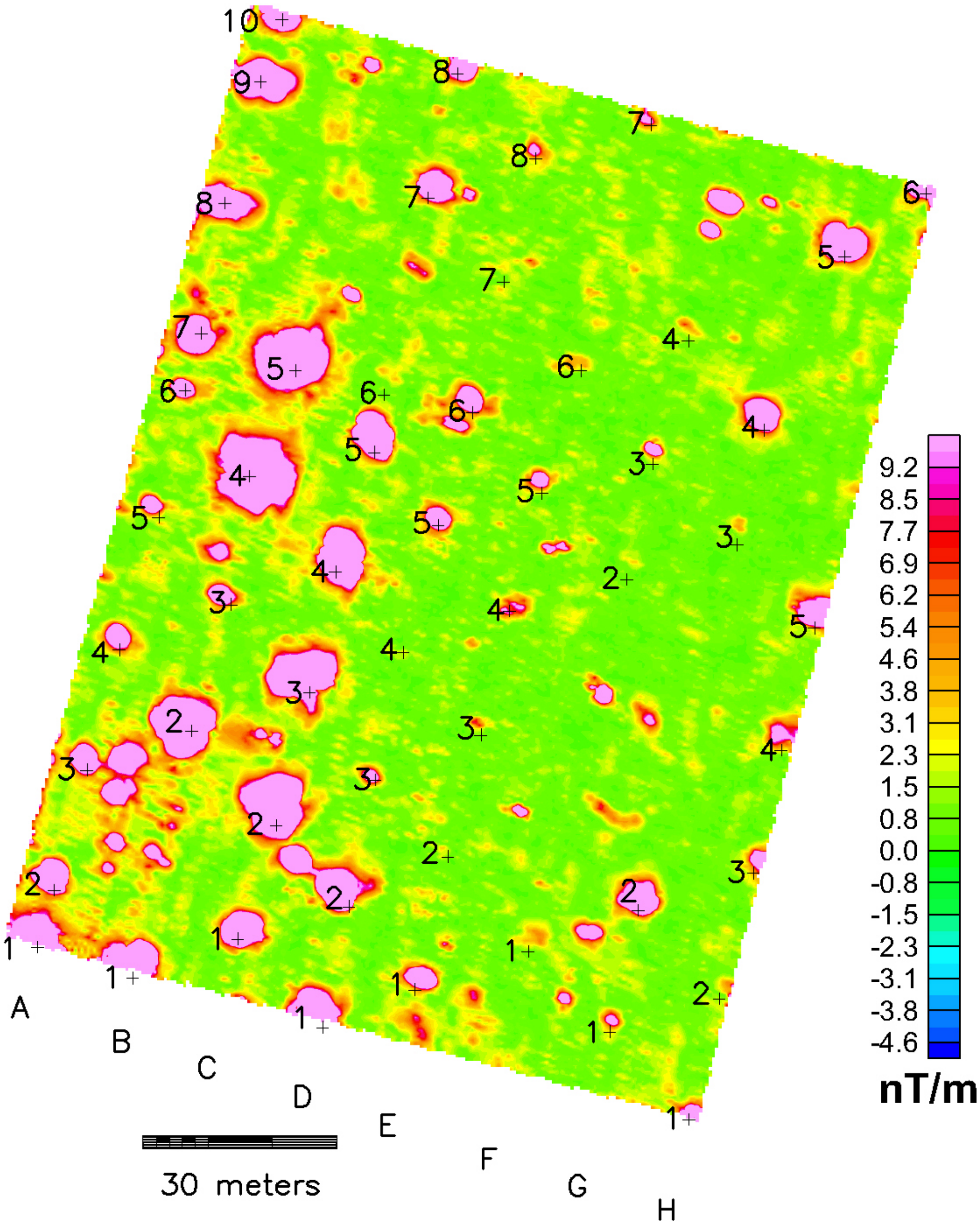

Figure 12. Analytic Signal Derived from Ground-Based Magnetometer Bottom Sensor (G858), BBR Test Grid.

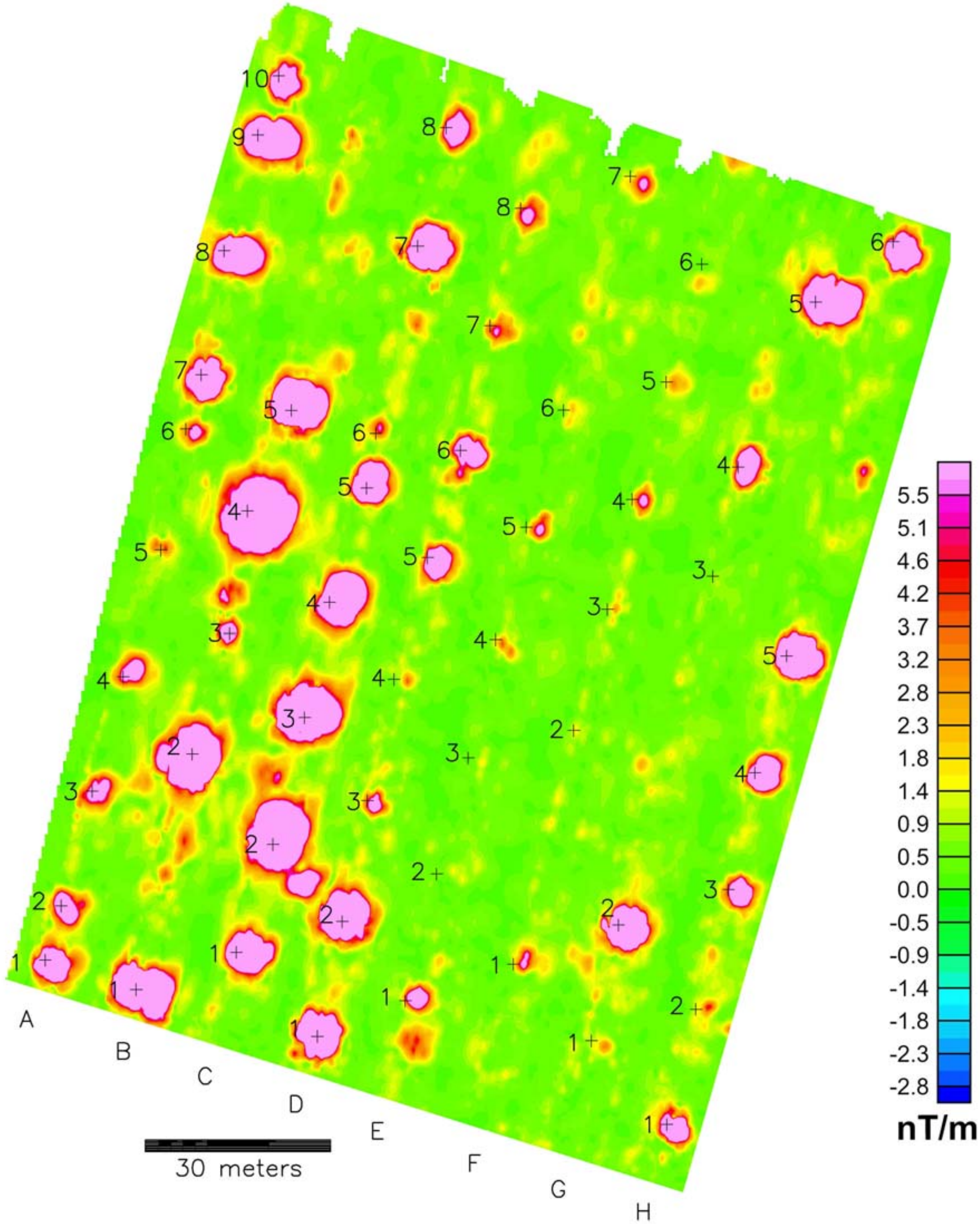

Figure 13. Analytic Signal Map Derived from Airborne (ORAGS-Arrowhead) Magnetic Data, BBR Test Site, September 2002, for Comparison with EM Results.

Figure 8 shows data acquired at the test site with the large loop configuration. This configuration had single wire loops affixed to the top and bottom of the 3m x 3m outer segment of the boom tubes. At low altitudes, the large loop receiving coils average the response over a larger area of the ground surface than do the small receiving coils, so full coverage of the test site can be accomplished with a larger line spacing. As with Figure 7, only the response from the first time sample ending at 93 μs is shown here.

Figures 9 through 13 show results from previous magnetic and EM surveys of the BBR test site for comparison with Figures 7 and 8. Figure 9 shows results from a ground-based EM61 survey of the site. Figures 10 and 11 show results from the first prototype survey that was conducted at the test site in September 2000 with the ORAGS-EMP (EM-61AB sensor) system. Figures 12 and 13 show ground-based and airborne magnetic surveys of the site for comparison with the magnetic data.

4.3.1.2 Signal/Noise Comparison to Other Systems from BBR Test Site Data

A SNR assessment was done to compare the performance of the different system configurations that were tested. Identifications for these configurations used in the remainder of this report are listed in Table 3. Basic configuration notations follow the format “Receiver type,” “Transmitter type,” “Base frequency,” “Special.”

Background noise was quantified as the first standard deviation from filtered, leveled measurements of the first time gate in an area where no UXO were buried, and the UXO signal was taken as the anomaly peak minus the background for the first time gate. SNR results are tabulated in Table 4. The SNR are not corrected to a constant target-to-receiver vertical offset, nor was an effort made to find the best SNR for a given target (typically achieved when the receiver passes directly over the target). Analysis of the data shows the small isolation-mounted receivers, with the large rectangular transmitter at 270-Hz base frequency configuration, had the best overall performance of those configurations tested. Comparison of Figures 7 through 13 indicates that this configuration is among the best overall.

The best helicopter EM configuration shows higher SNR in comparison with the ground EM61 by a factor of 6.2 times for the M-38 practice bomb and 2.7 for the 250-lb bombs. For smaller UXO, helicopter SNR were comparable for the best helicopter data (typically the isolated small coil receiver data) and the differential EM61 responses.

4.3.1.3 Altitude and Signal/Noise Assessment for Specific Ordnance Types

4.3.1.3.1 Signal/Noise Ratio Estimation Method

This section contains the methodology used to estimate SNR as a function of sensor-to-target vertical offset from the BBR test site dataset for various system configurations and EM targets. Data were acquired at sensor heights ranging from 1.0m to over 3m (generally 1.0-1.5m, but with some higher altitude tests), and targets were buried at depths ranging from 0 to 1.3m.

Table 3. ORAGS-TEM Configurations (distinguishing attribute is italicized).

Configuration Name(s)‡	Description	Base Freq.	Receiver Coil Type	Receiver Geometry	Transmitter Configuration
L-Rect-270, L-Rect-270-Diff	Large loop at one base frequency (270 Hz) in single-coil or differential (gradient) configuration	270Hz	Large loops	Centered at 4.5m from CL (on bridge)	Rectangular
S-Rect-270, S-Rect-270-Diff	Small coil at high base frequency (270 Hz) at 1 m alt in single-coil or differential (gradient) configuration	270Hz	External, small coils, total field and vertical difference	Centered at 4.5m	Rectangular
IS-Rect-270 IS-Rect-270-Diff	Isolation-mounted small coils at high base frequency (270 Hz) at ALASA* in single-coil or differential (gradient) configuration	270Hz	*Isolation-mounted* external, small coils	Centered at 4.5m	Rectangular
S-Rect-90	Collect survey data at *low base frequency (90Hz)* at ALASA	90 Hz	External, small coils, total field and vertical difference	Centered at 4.5m	Rectangular
L-Rect-90	Large loop at 90 Hz base frequency	90 Hz	Large loops, vertical field component	Centered at 4.5m	Rectangular
L-Slob-270	Lobed symmetric data at high base frequency (270 Hz) at ALASA	270Hz	Large loops, vertical field component	Centered at 4.5m	*Lobed symmetric*
L-Alob-270	Lobed anti-symmetric data at high base frequency (270 Hz) at ALASA	270Hz	Large loops, vertical field component	Centered at 4.5m	*Lobed anti-symmetric*
IS-Rect-270-3m	Place external (standard and vertical gradient), isolation-mounted coils, mounted on bridge, closer to helicopter to determine noise effects	270 Hz	External, small coils, total field and vertical difference	*Centered at 3m*	Rectangular
IS-Rect-90	Isolation-mounted small receiver coils at 90 Hz base frequency	90 Hz	Small coils	Centered at 4.5m	Rectangular
L-Rect-270-dual	Place coils on opposite sides of helicopter to ascertain symmetry in noise	270 Hz	Large loops	Centered at 4.5m *on both sides of aircraft*	Rectangular
L-Rect-270 L-Rect-270-Diff	Large loop coils at Bombing Target 1, BBR	270 Hz	Large loops	Centered at 4.5m	Rectangular
S-Rect-270 S-Rect-270-Diff	Small coils at Bombing Target 1, BBR	270 Hz	External small coil vertical component with vertical gradient	Centered at 4.5m	Rectangular

‡ Basic configuration notations follow the format 'Receiver type'-'Transmitter type' – 'Base Frequency' – 'Special'.
* ALASA = As low as safely achievable

Table 4. Calculated SNR for Items in Line C of the BBR Test Site.

Item	C1	C2	C3	C4	C5	C6	C7	C8	
Description (following Table 4.2)	**100 lb bomb fragments**	**250 lb bomb simulant**	**250 lb bomb simulant**	**100 lb bomb intact**	**100 lb bomb fragments**	**2.75 in rocket nose section**	**155 mm round**	**105 mm round**	**Average SNR**
Ground EM61 Differential	55	90	406	56	64	10	26	10	89.6
Arrowhead Magnetic System	48	288	500	115	56	4	100	24	141.9
L-Rect-270	91	134	368	109	86	9	20	11	103.5
L-Rect-270-Diff	43	57	193	57	50	2	14	7	52.9
L-Alob-270	52	75	149	55	34	5	7	2	47.4
S-Rect-270	80	98	333	48	42	2	13	4	77.5
S-Rect-270-Diff	46	42	192	19	19	1.5	8	2	41.2
IS-Rect-270	295	247	652	219	171	10	33	7	204.3
IS-Rect-270-Diff	342	209	472	231	94	11	26	1	173.3
S-Rect-90	13	31	175	11	10	2	5	2	31.1

Data for each EM configuration were drift corrected by removal of long-wavelength features, which appeared to be geologic in origin. The data as recorded comprised “target” anomalies arising from isolated conductors overlaid on a response arising from EM induction in the soil. This “ground response” was strongly altitude-dependent, so that small variations in sensor height generated significant anomalies, particularly at early delay times. These ground responses were strong enough to complicate gridding of the data. Fortunately, the target anomalies and the ground responses displayed distinct length scales, with the target responses exhibiting sharp, narrow anomalies, in contrast to the long scale length of the ground response anomalies. Preparation of the gridded anomaly maps was therefore preceded by a long-wavelength anomaly suppression procedure for each receiver component and delay time. In the first step of this procedure, anomaly peaks were located within the time series. These anomalies were then removed by interpolating a straight line through the neighborhood of each peak. The interpolated time series was low-pass filtered to yield a smoothed estimate of the long-wavelength features, which was subtracted from the original time series to approximately remove long-wavelength anomalies from the data. This procedure proved highly effective for the BBR data sets.

The filtered data were then divided by the standard deviations of those data, as observed along representative “clean,” low-level passes over portions of the test area that did not contain seeded targets, to yield SNR estimates at each sample location for all profiles and for all data bins. Noise levels in the “clean passes” were undoubtedly exaggerated by ground and contaminant response during this procedure; however, it was desirable to perform these low-altitude estimates to capture the level of vibrational noise present at these heights. It was observed that low-altitude noise levels were lower by as much as a factor of two at the eastern end of the test grid as compared to the western end, but to keep the SNR estimates conservative, the standard deviations used for SNR estimation were obtained at the noisier western end. The long-wavelength-removal method occasionally underestimates peak response amplitudes when the width of the anomaly above the detection threshold is large enough to “leak” into the smoothed long-wavelength estimate. Also, because the amplitude of the surrounding ground response has been subtracted from the target anomaly’s amplitude by this long-wavelength removal procedure, the SNRs of weak anomalies are typically underreported in areas of more conductive soil. For some coil configurations and (small) target types in this dataset, SNRs computed after application of this tool can be underestimated by a factor of two or more, rendering such SNRs moderately to highly conservative.

Peak SNR values were “picked” from profile plots and correlated with specific targets at known depths and locations. These peak SNR values were plotted, for each EM configuration and target type, versus sensor-target distance on log-log axes, as shown in Figure 14 for a 250-lb bomb target at 270 Hz base frequency.

“Bounding lines” representing maximal observed values of SNR for a given EM configuration and target type were estimated as power-law relationships of the form SNR_{peak}=A x H^B, where A is an Amplitude Scaling factor and B is an exponent. In most cases, different B values are required for different height ranges to represent the variation in response in those ranges. These bounding lines are indicated in Figure 14 for a 250-lb bomb target, as measured by the system configuration incorporating small receiver coils, isolation-mounted at 4 m from the helicopter centerline, with the large 3-m x 12-m transmitter operating at 270 Hz. The A and B values for each EM configuration, height range and target type are listed in Table 5.

As indicated above, SNR estimates derived in this manner are based on signal amplitudes following long-wavelength removal, this being the critical measure of the sensitivity of the system to isolated conductive targets. The estimated system sensitivity, particularly to small targets, is thus conservative, with SNR estimates being underreported by as much as a factor of two in some cases.

4.3.1.3.2 SNR Variation with Height

In Figure 14, the strong SNR values for the 250-lb bomb target type permitted estimation of the SNR variation over a considerable height range. This clearly highlights the break between SNR falloff at heights smaller than or comparable to the smallest transmitter dimension of 3 m (proportional to ht^{-4}) and in the 4-5 m range (proportional to ht^{-6}).

It should be reiterated that the bounding lines represent the “best” SNR performance observed for a particular data bin (Bin 1), a given base frequency (270 Hz), and a given combination of target type and system configuration. This “best performance” represents the case where the transmitter-target-receiver coupling is maximized. Descriptors for these 250-lb bomb stimulant data are therefore Exp=-4 with an Amplitude Factor of 15,000 at low altitudes, and Exp=-6 with an Amplitude Factor of 90,000 at high altitudes. Note that for large-loop receivers (not shown on Figure 14), the exponent was found to be approximately -2 at low altitudes, where the dimensions of both the transmitter and receiver loops are larger than the sensor-to-target height.

In Table 5, the descriptors for each boundary line (defined in the previous section) are given as the height exponent (column 2) and an amplitude coefficient for each target type (columns 3-14).

These descriptors are listed for the transmitter-receiver configurations and base frequencies indicated by the "Configuration ID" shown in column 1 and defined in the previous section. The expression for the boundary line pertaining to a particular target and height range is constructed by extracting the height exponent *E* from column 2 and the amplitude coefficient *A* for the particular target and configuration ID. For a target-to-sensor height of *h*, the boundary line expression is then

$$SNR_{\max} = A \cdot h^{E}$$

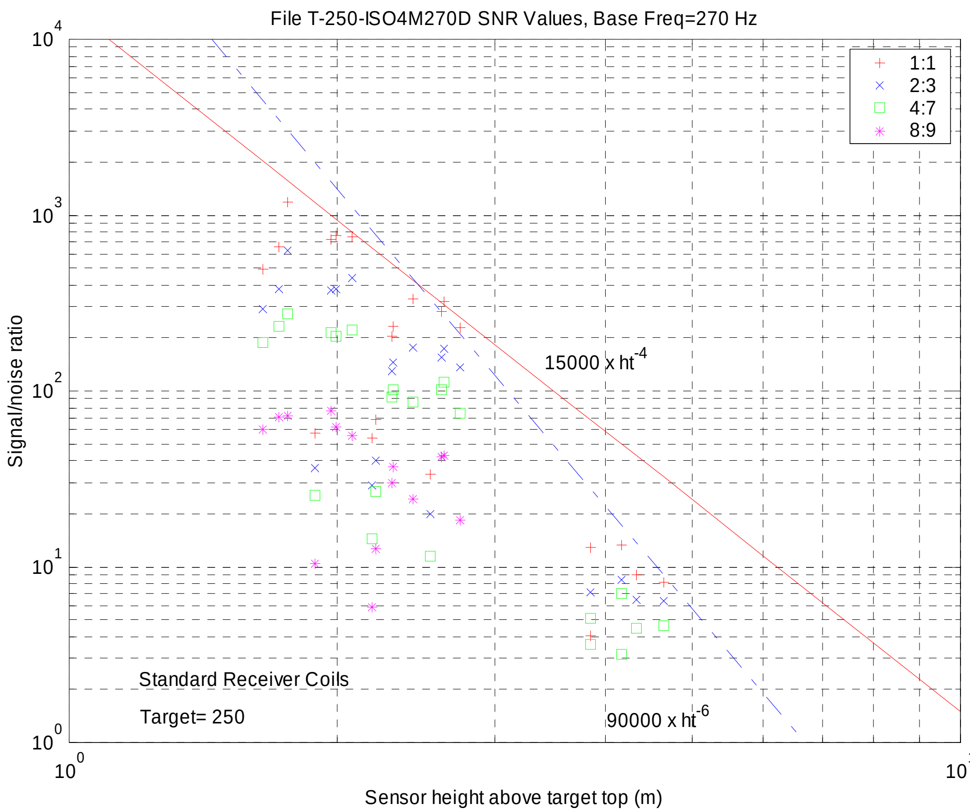

Figure 14. Signal/Noise Estimates Versus Sensor-to-Target Height for the 250-lb Bombs (inert and simulants) **on the BBR Test Grid During the 2002 Field Trials for Bin 1 Responses of the 270 Hz, Isolation-Mounted Standard Receiver Coil Configuration.** (The legend lists the EM samples in each bin, starting with Bin 1 [red cross symbol], which consists of samples from 1 to 1 [i.e., only the first sample]. Bin 2 comprises samples 2 to 3, and so on. Sample 1 begins at the end of the transmitter ramp and is 93 microseconds long.)

Table 5. Signal/Noise Descriptors for Various ORAGS-EM Configurations at BBR Calibration Test Grid.

Configuration ID	Exp	Amplitude Factors for Specified Targets											
		250	M-38	155	105	2.75	81mm	61mm	60mm	Stove Pipe	Al Sheet	Nail	Al Rod
IS-Rect-90 (low)	-4	10000	5500	550	290	270				600			
IS-Rect-270 (low)	-4	15000	5500	650	420		115	115	70	5000	700	22	
IS-Rect-270 (low)	-4	5000	1250	250	170	110				1500			
S-Rect-90 (low)	-4	5300	1250	270	165								
S-Rect-270 (low)	-4	8500	2750	750	240	190	92	72		1950		44	
IS-Rect-270 (high)	-6	90000	33000										
S-Rect-270 (high)	-6	75000	24000	6000									
IS-Rect-270-Diff (low)	-5	20000	7000	800	530	270	150		35	7000			
S-Rect-270-Diff (low)	-5	16000	3000	750	220	85	160			1000			
L-Rect-90 (high)	-4	3800	980	110	70					650			
L-Rect-270 (high)	-4	5000	1400	250	100	55	55	24	15	1450		5	
L-Rect-270 (low)	-2*	650	320	90	35	30	21	16	11	320		4.5	
L-Rect-270-Diff	-3	1100	320	80	35	44	36			950		14	
L-Rect-270 (high)	-4	4800	1150	210	120	45	55			15	560		
L-Slob-270 (high)	-4	4200	1200	130	95	40	60	18	12	1000			20
L-Slob-270 (low)	-2*	950	300	45	33	25	25	9	10	230			10
L-Alob-270 (high)	-4	8000	2200	350	230	400							
L-Alob-270 (low)	-2*	1420	600	75	53	48		25					

*Power-law falloff exponents of –2 were indicated on inspection of these records when flying at low altitude with large loops. The ratio of loop dimension to target distance is large for these measurements, resulting in a low order falloff.

For example, for the Iso4m90 configuration, the descriptors are *A*=5500 and *E*=-4, so the bounding line for the M-38 at a target-to-sensor height of 1.5m is described by

$$
\begin{aligned}
SNR_{\max} &= 5500 \cdot h^{-4} \\
&= 5500 \cdot 1.5^{-4} \\
&= 1086
\end{aligned}
$$

This value describes the best SNR expected (usually found in the shortest time bin) for the specified target-to-sensor height, system configuration, and target type.

Table 6 indicates the estimated maximum SNR values for two selected target-to-sensor vertical distances: 1.5m and 4m. The maximum for a selected vertical distance is identified as the top edge of a cloud of SNR measurements on log-log coordinates. The SNR_{max} estimate of 1086 computed in the example above may be found in the first row, fourth column of this table, corresponding to the M-38 target at 1.5m below the sensor for the Iso4m90 configuration. The practical detection threshold for profile data should occur for SNR values on the order of 3; below this level, the FPs rate climb rapidly, so this project considers items with SNR larger than 3 to be "detectable." Note that spatial correlation effects in map presentations further reduce the detection threshold for such presentations. If further improvements in system noise are obtained, SNRs will be increased, bringing more targets above the detection threshold for a given EM configuration and height.

The lower height represents the case where the system is flown over near-surface targets, with a sensor-to-target distance of 1.5m. Zero values of SNR in this case indicate that values of A and B were not determined for the combination of EM configuration and target type indicated. The upper height of 4 m represents the case where targets are deeply buried or the system altitude is relatively high due to vegetation or other obstructions.

Due to the build-up of uncertainties in the estimation of these SNR values, differences of 10% or less in SNR between different EM configurations for a given target should not be given much weight, but differences of 50% or more are considered to be significant, particularly for large values of SNR. At low altitude/shallow depth, most ordnance targets appear to be detectable. The most sensitive configurations, ranked by SNR values for strong targets at the 1.5 m target-to-sensor height, were as follows:

- IS-Rect-270 and IS-Rect-270-Diff, followed by
- S-Rect-270-Diff,
- IS-Rect-90,
- S-Rect-270 and S-Rect-90,
- IS-Rect-270-3m,
- L-Alob-270,
- L-Slob-270,
- L-Rect-270,
- L-Rect-270-Diff.

Table 6. Signal-to-Noise Estimates for 1.5-m and 4-m Sensor-Target Distance.

Maximum Target SNR (frac) for Target-Sensor Distance=1.5m											
		Target ID									
Configuration ID	**Exp't**	**250**	**M38**	**155**	**105**	**2.75**	**81mm**	**61mm**	**60mm**	**Stove Pipe**	**Nail**
IS-Rect-90(low)	-4	1975	1086	109	57	53	0	0.0	0.0	118.5	0.0
IS-Rect-270 (low)	-4	2963	1086	128	83	0	23	22.7	13.8	987.7	4.3
IS-Rect-270-3m (low)	-4	988	247	49	34	22	0	0.0	0.0	296.3	0.0
S-Rect-90 (low)	-4	1047	247	53	33	0	0	0.0	0.0	0.0	0.0
S-Rect-270 (low)	-4	1679	543	148	47	38	18	14.2	0.0	385.2	8.7
L-Rect-270 (low)	-2	289	142	40	16	13	9	7.1	4.9	142.2	2.0
L-Slob-270 (low)	-2	422	133	20	15	11	11	4.0	4.4	102.2	0.0
L-Alob-270 (low)	-2	631	267	33	24	21	0	11.1	0.0	0.0	0.0
IS-Rect-270-Diff	-5	2634	922	105	70	36	20	0.0	4.6	921.8	0.0
S-Rect-270-Diff	-5	2107	395	99	29	11	21	0.0	0.0	131.7	0.0
L-Rect-270-Diff	-3	326	95	24	10	13	11	0.0	0.0	281.5	4.1

Maximum Target SNR (frac) for Target-Sensor Distance=4m											
		Target ID									
Configuration ID	**Exp't**	**250**	**M38**	**155**	**105**	**2.75**	**81mm**	**61mm**	**60mm**	**Stove Pipe**	**Nail**
		22.0	8.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S-Rect-270 (high)	-6	18.3	5.9	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
L-Rect-90 (high)	-4	14.8	3.8	0.4	0.3	0.0	0.0	0.0	0.0	2.5	0.0
L-Rect-270 (high)	-4	19.5	5.5	1.0	0.4	0.2	0.2	0.1	0.1	5.7	0.0
L-Rect-270-Dual (high)	-4	18.8	4.5	0.8	0.5	0.2	0.2	0.0	0.0	0.1	0.0
L-Slob-270 (high)	-4	16.4	4.7	0.5	0.4	0.2	0.2	0.1	0.0	3.9	0.0
L-Alob-270 (high)	-4	31.3	8.6	1.4	0.9	1.6	0.0	0.0	0.0	0.0	0.0

Only the larger ordnance targets, such as 250-lb bombs and M-38s, were typically detectable at the 4m target-sensor vertical distance. The order of sensitivity in this case was different, due to the lower attenuation rate of the LL relative to the small-coil receivers in this height range:

- L-Alob-270,
- IS-Rect-270,
- L-Rect-270,
- L-Rect-270-Dual,
- S-Rect-270,
- L-Slob-270, and
- L-Rect-90

Based on these observations, it appears that the most sensitive configuration for measurements in the 1-3m sensor-target distance range tested at BBR used vibration-isolated small-coil receivers. The distance between the small-coil array and the helicopter CL was a significant factor-the coils mounted at 3m from CL were substantially less sensitive than the coils mounted at 4m from CL. This effect appears to be due to clipping of the earliest time bins by the acquisition system, caused by the increased helicopter anomaly at the 3m position. Later time bins were not affected.

The antisymmetric lobed transmitter configuration was substantially more sensitive (Table 5) than the best rectangular-transmitter, large-loop receiver configuration over the full altitude range and was also substantially more sensitive than the symmetric lobed transmitter.

4.3.1.4 <u>Summary of Data Analysis from BBR Test Site</u>

The following represent summary observations regarding detection and SNR from the BBR Calibration Test Site configuration tests:

1. The large loop and small loop configurations have similar response at the test site. The small loop receiver produced higher SNR than the large loop receiver at target-receiver distances below 2m. At intermediate target-receiver distances (2-3m), the performance of the two receiver coil configurations were comparable. For target-receiver distances above 4m, the large loop receivers appear to be favored. The small loop may be better suited for detecting the smallest targets, whereas the large loops have reduced risk of spatial aliasing, due to their intrinsic spatial averaging, and they are simpler, lighter, and require no special mounting techniques.

2. Performance of the most effective configurations of the ORAGS-TEM system at the 1.0-1.5m altitude is comparable to the performance of the ORAGS airborne magnetic systems. Comparison of Figures 7 and 8 with the ORAGS-Arrowhead result in Figure 13 indicate that the ORAGS-TEM performed similar to the ORAGS-Arrowhead.

3. The performance of all ORAGS-TEM small loop and large loop configurations is considerably better than the previous ORAGS-EMP (EM-61AB) surveys. Noise levels are much lower, and smaller targets appear above the noise floor. The SNR approaches and occasionally exceeds that of the airborne magnetometer system, and at the lowest

altitudes, exceeds the performance of the ground-based EM61 for many targets, as shown in Table 4.

4. Gradients provided slightly greater sensitivity at low altitudes with the small receiver loops. They produced mixed results with the large receiver coils (not shown here). EM gradient data can be used in conjunction with single loop data as a depth discriminator because gradient response decays faster with burial depth than single loop response. Shallow UXO may give strong gradient and single loop responses whereas more deeply buried objects may appear only on the single loop maps.

The principal SNR results indicate that:

1. At low altitudes, the small coils, when isolation-mounted, yielded almost twice the SNR of the rigidly-mounted small coils, and four to six times the SNR of the best large-loop configurations. For the isolated versus rigid-mounted small-coil comparison, the twofold improvement is entirely due to a decrease in noise. The small coils generate approximately three times stronger but narrower anomaly than do the large loops for targets tracking directly beneath the center of the coil, and the isolation-mounted small coils display approximately one and a half times lower noise than the large loop.

2. At relatively high altitude (4m sensor-target separation), the best large-loop receiver configuration yielded substantially higher SNR than did any of the small-coil configurations.

3. The antisymmetric lobed-transmitter, large-loop receiver configuration yielded higher SNR than did the other large-loop receiver configurations.

4. The best vertical difference mode (isolated small-coil array at 4m from helicopter centerline) was comparable to the best small-loop mode at a sensor-target distance of 1.5 m but degraded much more rapidly with height than did any of the other configurations.

5. For bombs, the best helicopter SNR exceeded the SNR from the ground EM61 system. For smaller ordnance, helicopter SNR was comparable to or lower than ground EM SNR.

The improvement in low-altitude small-coil SNR, compared to the results of earlier shakedown tests, was initially surprising. This improvement is attributed to two factors—the isolation mounting of the small coils and their location at increased distance from the transmitter cable. When the isolation mounts were removed but the small coils were left at 4m from the helicopter CL, the SNR values at low altitude dropped but remained much higher than the large-loop receiver results. This corroborates ground test results, which indicated that signal levels from the small coils were higher than those from the large loops, particularly at low altitudes, provided that the small receiver coils tracked within .5m of the target and that the receiver coils were spatially separated from the transmitter coil. Thus, the strength of the small-coil configuration is that it yields higher signal levels when the coil passes directly over the target, while its weaknesses are that the coils are more vulnerable to noise generation arising from coil vibration and therefore require vibration isolation, and they must be located away from the transmitter cable.

The strengths of the large-loop receiver configuration are that its footprint is larger and its sensitivity does not drop as rapidly with respect to height as does the small-coil configuration. The 3-4m target-sensor distance is the approximate crossover range. Thus, if large objects are sought in areas where the sensor coils cannot be flown at ground clearances of less than 2-4m (depending on target depth below surface), the large loop configuration may be preferable unless further improvements are achieved in isolation-mounting of small-coil receivers and a denser array of small-coil receivers is used. Fortunately, it will not be necessary to select one method over the other prior to construction of the final system because of the ease with which large-loop receivers may be mounted on the booms.

Finally, *at the present state of development*, vertical difference results are useful for detection of surface objects and discrimination of surface objects from deeper ones, provided that low survey altitudes can be maintained. Maps generated from the difference results had other advantages, particularly in cluttered zones where their increased lateral resolution was an asset, so further development of this approach would be desirable to accommodate similar situations.

4.3.2 Results from Bombing Target 1

In addition to the tests at the BBR Test Site, large and small receiver coil data were also acquired at Bombing Target 1 at BBR. At Bombing Target 1, approximately 14 hectares were surveyed with the large-loop receiver configuration, and a smaller area, approximately 2.4 hectares, was covered with a small-coil system. These results are discussed in detail in the project Final Report, and will not be reiterated here.

4.4 TECHNICAL CONCLUSIONS

The primary goal of this project was to evaluate parameters critical to the design of an airborne EM system capable of detecting a variety of buried ordnance. The basic design of the system is analogous to the previously developed helicopter magnetic systems, which are based on a frame-mounted, multiple sensor platform that permits the helicopter to fly within a few meters of UXO-contaminated terrain and thus attain a high level of detection and positional accuracy. The results presented in this report show that this goal has been achieved. The BBR field tests enabled the establishment of base frequencies for the system—90 Hz and 270 Hz—that allowed the highest SNR for the given system. Using these frequencies, we were able to combine different transmitter configurations, receiver types and positions to find the combinations that gave the highest SNR. We demonstrated that, under good field conditions, the helicopter EM system is capable of producing data of a quality that approached or exceeded ground-based EM survey results and ORAGS-Arrowhead airborne survey results. At a 1-m survey altitude, we were able to detect objects as small as 60-mm mortar rounds, a level of detection equivalent to that of the ORAGS helicopter total field magnetic systems.

The sensitivity of the ORAGS-TEM system proved to be well in excess of the proof-of-concept EM-61AB system (Doll et al, in press). At the BBR test site, the EM-61AB was able to detect 155-mm and 105-mm rounds but failed to detect 81-mm shells and smaller items. At the lowest survey altitude over the same test site, the ORAGS-TEM system reliably detected both the 81-mm and the 60-mm mortar rounds. In field operation, we anticipate that a smaller percentage of 60-mm rounds would be detected, and that this sensitivity would be even more altitude-dependent than for magnetometer systems. To achieve this degree of resolution was not a straightforward process; the BBR field tests produced excellent results because of lessons learned from results of prior shakedown flights in Ontario, Massachusetts, and New Mexico (Beard et al, 2002a, 2002b).

The EM response of ordnance is more complicated than its magnetic response, and the falloff in response with increasing altitude does not follow the $1/R^3$ decay of magnetic fields in the presence of compact bodies, where R is the source-receiver distance and 3 is the decay exponent. As shown in Table 5, the decay exponent can vary from 2 to 6 according to the transmitter-receiver configuration and the survey height. Below 1.5-m survey height, we found that vertical gradient receivers usually produced superior signal-to-noise than single loop receivers. However, because the decay of the vertical gradient field is more extreme than that of the single loop, single loop receivers were as good as or superior to vertical gradient receivers above 1.5-m. This is in contrast to the magnetic gradiometer which has a better signal-to-noise than the total field due to rejection of the helicopter common mode noise, which has a magnetic rather than EM source. Decay exponents greater than 3 imply more rapid field decay than would be found in magnetic data; therefore, magnetic systems such as the ORAGS-Arrowhead may have an advantage over EM systems where survey altitudes exceed a few meters. There are about three times more magnetic anomalies above the noise floor at Bombing Target 1 than EM anomalies, although we reiterate that the EM system used in this comparison has lower SNR than the optimal configurations that were tested at the BBR Test Site. Because a fence runs through the middle of the target area, and a raised circular berm defining the target, a portion of the survey was conducted at heights of more than 3m. At this altitude, the EM response of many small items falls below the noise threshold, whereas small magnetic signals can still be detected. There is a weak positive correlation between the size of the magnetic anomaly and the magnitude of a corresponding EM anomaly.

A system to detect small UXO would use a different base frequency than one designed to discriminate the type of target. Low base frequencies produce excellent EM response and a longer decay time over large targets but, in moving systems, give poor SNR over smaller targets because too few transmission cycles occur to define the target. High base frequencies produce better SNR for smaller targets, but the decay time may be too short to define the time constant of the target. We found that with a 270-Hz base we could detect 60-mm mortars, but estimates of the time constants associated with these and with larger targets were inconsistent because the time between transmissions was too short to get an adequate decay curve. At 90-Hz base frequency, the SNR of the 60-mm mortars decreased, but time constant estimation for larger ordnance was more consistent. At 90 Hz, thick-shelled objects such as 155-mm rounds produced consistently larger time constants than smaller, thin-shelled items. An understanding of this behavior is helpful in setting acquisition parameters for a particular survey.

A number of different factors contributed to the success of the ORAGS-TEM system. Incremental improvements in system electronics, especially suppression of early time noise and faster transmitter turnoff, contributed to an enhanced SNR. Vibration isolation improved small-coil receiver data. Careful analysis of power spectra at different base frequencies enabled us to find those frequencies that gave the highest SNR for ordnance anomalies. Experiments with transmitter and receiver geometries and styles, including vertical gradient receivers, also improved data quality. We should emphasize that, besides these project-specific considerations, the success of this project relied in large part on the cumulative knowledge obtained in development of airborne magnetic systems for UXO detection.

In its current configuration, the ORAGS-TEM is a two-channel system. This was adequate for comparing one configuration with another but is inefficient for "production" surveys because the swath width is small and requires interleaving and precise positioning in order to fully survey a site. Similar magnetic system tests have demonstrated that interleaving and variations from one flight pass to the next results in a degrading of data quality. The cost for expanding from a two-channel to an eight-channel system is relatively small, as it will only require construction of more receiver channels in the existing console, as well as several new coils and preamplifiers. The BBR demonstration provided a thorough evaluation of several system configurations and comparison with previous airborne magnetic and EM systems but did not exploit the strengths of EM systems in environments where magnetic systems fall short.

5.0 COST ASSESSMENT

5.1 FACTORS AFFECTING COST AND PERFORMANCE

The cost of an airborne survey depends on many factors, including:

- Helicopter service costs (which depend on the cost of ferrying the aircraft to the site), fuel costs, terrain and vegetation conditions impacting flight line configuration and turn-around, etc.
- Total size of the blocks to be surveyed
- Length of flight lines and amount of interleaving
- Extent of topographic irregularities or vegetation that can influence flight variations and performance
- Ordnance objectives, which dictate survey altitude and number of flight lines
- Temperature and season, which control the number of hours that can be flown each day
- Location of the site, which can influence the cost of logistics
- Number of sensors and their spacing; systems with too few sensors may require more flying, particularly if they require interleaving of flight lines
- Survey objectives and density of coverage, specifically high density for individual ordnance detection versus transects for target/impact area delineation and footprint reduction.

5.2 DEMONSTRATION COST

The total cost of this demonstration and evaluation project was $1,101,579. Several test data sets were acquired at the BBR Test Site and cannot be used appropriately to derive cost per acre estimates. At Bombing Target 1, ORAGS-TEM was flown with two different receiver configurations. With the two small-coil receivers mounted in a vertical gradient configuration on the starboard side of the helicopter (configuration IS-Rect-270), a narrow 5.6-acre swath about 36.5-m wide was flown in a period of 64 minutes using 28 flight lines spaced at about 1.3 m. With the small loop receivers, the lines were racetracked, i.e., the pilot returned to the south end of the swath to begin each line. Data were also acquired at BT-1 in a “production” mode, although it must be recognized that the current two-channel configuration of the system does not allow for efficient production operation. The configuration, designated L-Rect-270, consisted of two large loop receivers with one mounted on the port and one on the starboard side of the helicopter. In this production mode, 34.5 acres were covered in 77 minutes of flying with 56 flight lines. With the large loop receivers, alternate lines were flown in opposite directions. Overlapping of flight lines was required. However, it must be noted that this was a research project, and not a production survey. Several areas were flown more than once, and all areas were very small by airborne survey standards.

The total project required 35.5 hrs of helicopter airtime, including mobilization and demobilization over 20 days, but only 1.25 hrs were actually spent collecting the 34.5 acres of production acquisition (38 line km of flying). The remainder of the time was spent on mobilization and demobilization, on ferry flights to and from the site, on flights for refueling, on various calibration and experimental runs, on turnarounds at the end of lines, and on reflights due to inadequate data quality. In addition, costs associated with the modification to and installation of the seeded items at the Calibration Site are *not* included in the total cost for the project. The actual project demonstration costs are presented in Table 7.

5.3 TYPICAL AIRBORNE SURVEY COSTS

Table 8 represents the costs associated with the airborne-based technology in a typical survey implementation when operated at the scale of a production survey. The scale of the survey for this cost profile is a 2,000-acre site, significantly larger than the original area surveyed during the project demonstration. All costs represented in the table are costs that would be incurred only for a production demonstration at a typical survey site and do not reflect any costs associated with the demonstration of an innovative technology. It is important to note that cost associated with excavation for ground-truthing and verification is *not* included in this cost profile.

Also of note, no one-time, demonstration-related costs associated with survey optimization, detailed Calibration Site analysis, non-routine analysis, or excessive reflights over the survey areas to evaluate or refine the demonstration are included in the costs outlined in the table. Although these costs are not included, the cost/acre is still quite high due to the small survey size and the current configuration of the system. Operation of a two-channel system requires a high level of interleaving, which makes for very inefficient and costly production surveys. Reasonable efficiencies (better than ground survey costs) can be achieved when the survey size is approximately 2,000 acres and when a larger number of receiving channels is used to cover a larger area with each swath.

This estimate assumes an ORAGS-TEM array configuration consisting of four distinct receiver channels. Flight line spacing is assumed to be 8 m, resulting in an interleaving between adjacent survey lines. Costs estimates are based on experience with the ORAGS-Arrowhead and are reasonably accurate. Production efficiencies have been altered to account for differing acquisition rates based on survey speed and altitude, but hourly helicopter and crew costs remain the same.

These generic cost estimates include the following factors:

- Project management
- Mobilization/demobilization of the applicable airborne technology
- Data acquisition (including equipment and helicopter costs)
- Data processing, analysis, and interpretation
- Reporting
- Travel, materials, and miscellaneous expenses
- Federal acquisition cost (FAC) (3% congressionally mandated administrative fee to DOE)
- 5% project contingency to account for weather, etc.

Table 7. Cost Assessment Table.

Cost Category	Sub Category	Details	Quantity	Cost[1]
Presurvey (Start-Up)	Site Characterization	**Site Inspection**		
		Toronto, ON	0 days	$0
		Hyannis, MA (includes hotel and per diem; airfare covered in corresponding Camp Wellfleet survey project)	1 day	$1,969
		Albuquerque, NM (includes hotel and per diem; airfare covered in corresponding Laguna/Isleta survey projects)	1 day	$1,869
		Pine Ridge, SD (includes hotel and per diem; airfare covered in corresponding Laguna/Isleta survey projects)	1 day	$1,869
		Mission Plan preparation & logistics (most covered under corresponding Camp Wellfleet, Laguna/Isleta, and BBR survey projects)	10 days	$17,690
		Calibration Site development (includes preseed and postseed ground-based surveys) at the following sites:		
		Toronto, ON	2 days	$6,618
		Hyannis, MA	2 days	$6,618
		Albuquerque, NM	0 days[2]	$0
		Pine Ridge, SD	0 days[2]	$0
	Mobilization	**Equipment/personnel transport (includes travel):**		
		Toronto, ON	2 days	$7,698
		Hyannis, MA	0 days[3]	$0
		Albuquerque, NM	0 days[3]	$0
		Pine Ridge, SD	0 days[3]	$0
		Helicopter/personnel transport (includes travel):		
		Toronto, ON	0 days[3]	$0
		Hyannis, MA	0 days[3]	$0
		Albuquerque, NM	0 days[3]	$0
		Pine Ridge, SD	0 days[3]	$0
		Unpacking and system installation:		
		Toronto, ON	1 day	$4,559
		Hyannis, MA	1 day	$4,559
		Albuquerque, NM	1 day	$4,559
		Pine Ridge, SD	1 day	$4,559

Table 7. Cost Assessment Table. (continued)

Cost Category	Sub Category	Details	Quantity	Cost[1]
Presurvey (cont'd)	Mobilization	**System testing & calibration:**		
		Toronto, ON	1 day	$6,309
		Hyannis, MA	1 day	$6,309
		Albuquerque, NM	1 day	$6,572
		Pine Ridge, SD	1 day	$6,747
Presurvey subtotal				**$88,504**
System Development & Capital Equipment[4]	Advisory panel	Nine persons, two meetings	1 each	$19,000
	Conceptualization & modeling	ORNL, USAERDC, Temple	1 lot	$175,754
	Design and construction (not including hardware)	Prototype and final systems	1 lot	$220,560
	Testing and assessment	Final system	1 lot	$50,000
	EM transmitter and receivers	$12,000 total cost	1 each	$12,000
	GPS	$15,500 total cost	1 each	$0
	Booms and mounting hardware	$16,500 total cost	1 set	$16,500
	Navigation system	$5,200 total cost	1 each	$0
	Laser altimeter	$7,300 total cost	1 each	$0
	Data management console	$31,200 total cost	1 each	$31,200
	GPS base station	$15,600 total cost	1 each	$0
	PCs for data processing & analysis	$3,450 total cost	2 each	$0
	Shipping cases	$2,375 total cost	3 each	$2,375
	Trailer	$3,600 total cost	1 each	$0
Capital subtotal				**$527,389**
Operating Costs (includes Toronto, Hyannis, Albuquerque, and Pine Ridge)	Equipment Rental	GPS equipment	1 each	$165
	Data acquisition	Helicopter time, including pilot and engineer labor	28 days (53.6 hours airtime)	$12,211
	Operator labor		23 days	$4,900
	Data processing	Geophysicist	28 days	$43,120
	Field support/management	Engineer/senior geophysicist	28 days	$49,532
	Hotel, per diem, rental car	Survey team	28 days	$15,107
	Airport landing fees		28 days	$700
	Data analysis and interpretation	Two geophysicists	54 days	$178,686

Table 7. Cost Assessment Table. (continued)

Cost Category	Sub Category	Details	Quantity	Cost[1]
Operating Costs (cont'd)	Project management		36 days	$63,684
	Reporting and documentation		18 days	$59,562
Operating cost subtotal				**$427,667**
Postsurvey	Demobilization	**Disassembly from helicopter, packing, and loading for transport:**		
		Toronto, ON	1 day	$4,559
		Hyannis, MA	1 day	$4,559
		Albuquerque, NM	1 day	$4,559
		Pine Ridge, SD	1 day	$4,559
		Equipment/personnel transport (includes travel):		
		Toronto, ON	2 days	$7,698
		Hyannis, MA	0 days[3]	$0
		Albuquerque, NM	0 days[3]	$0
		Pine Ridge, SD	0 days[3]	$0
		Helicopter/personnel transport (includes travel);		
		Toronto, ON	0 days[3]	$0
		Hyannis, MA	0 days[3]	$0
		Albuquerque, NM	0 days[3]	$0
		Pine Ridge, SD	0 days[3]	$0
Postsurvey subtotal				**$25,934**
Indirect environmental activity costs	Environmental and safety training[3]	8-hour Hazardous Waste Operations and Emergency Response (HAZWOPR) (includes the course cost)	0 days[3]	$0
Miscellaneous	Department of Energy Federal Acquisition Cost (FAC)	3% of project total; congressionally-mandated charge for administering the Work-for-Others (WFO) program		$32,085
Miscellaneous subtotal				**$32,085**
Total costs				**$1,101,579**

[1] Includes all overhead and organization burden, fees, and associated taxes.
[2] No costs were incurred for the establishment of Calibration Sites in Albuquerque, NM, and Pine Ridge, SD. Existing sites established under previous survey projects were used for system testing and development.
[3] These costs were included in related airborne magnetic survey projects occurring in conjunction with EM system testing and development (leveraged cost).
[4] Capital costs associated with many airborne system components and related equipment were acquired under other projects (e.g., development of airborne magnetic system) and are not included in the cost of this project (leveraged cost).

Table 8. Cost Estimate for a Typical Airborne-Based Survey of UXO Contamination.

Cost Category	Subcategory	Costs
Fixed Costs		
1. Capital Costs	Mobilization/Demobilization	$61,600
	Planning/Preparation/Health and Safety Plan (Mission Plan)	$3,000
	Equipment	$20,000
	Management Support	$17,600
	Subtotal	**$102,200**
Variable Costs		
2. Operation And Maintenance	Operator Labor	$95,000
	Labor for Data Processing, Analysis, and Interpretation	$30,500
	Instrument Rental or Lease	$10,000
	Helicopter Support Services	$120,400
	Travel and Miscellaneous Materials	$6,250
	Reporting	$5,000
	Subtotal	**$267,150**
3. Other Technology-Specific Costs	Excavation for Ground-Truthing and Verification	Not included
	Establish Calibration Site	Not included
4. Miscellaneous Costs	DOE FAC	$11,100
	Subtotal	**$11,100**
	Total Technology Cost	**$380,450**
	Throughput Achievable (acres per hour)	**$15**
	Unit Cost per acre	**$190**

5.4 COST ANALYSIS

The major cost driver for an airborne survey system is the cost of helicopter airtime. In terms of tasks, this constitutes most of the data acquisition costs, the single largest cost item.

Data processing and analysis functions made up the bulk of the remaining costs. The costs associated with development of robust processing algorithms were a major factor in this evaluation project. This is expected to diminish with each project as solutions to common scenarios are found. Mobilization is also a major task in terms of cost. Generally, this is a function of distance from the home base for the helicopter and equipment. Peripheral costs associated with this evaluation project, such as ground truth and excavations, were *not* considered in this part of the cost analysis.

The sensitivity of the overall cost to these drivers can be modeled under several different scenarios. Helicopter time on site is a factor of several variables. The first is the number and dimensions of the survey blocks. The greatest amount of nonsurvey time is spent in turns at the end of each line in preparation and alignment for the next line. Fewer and longer survey lines are therefore more efficient than many shorter ones.

The other major cost drivers were data processing and mobilization/demobilization. Processing and mobilization costs are generally linear with project size and transportation distance, respectively. Processing costs and data deliverable times will decrease with experience at multiple sites.

Continued and consistent use of a static technology could potentially lead to overnight delivery times. Mobilization costs are unlikely to decrease with time. The use of a local helicopter and pilot may offer decreased mobilization costs but risks significantly increased acquisition costs if the mechanic in charge of installation is unfamiliar with the equipment, or if the pilot is uncomfortable with the level of precision flying that is required.

5.5 COST CONCLUSIONS

For consideration of DoD-wide application of the airborne technology, a number of factors must be considered when evaluating the appropriateness of the airborne technology and potential for substantial cost savings. While initially impressive, it is not possible to simply apply these types of cost savings across the entire DoD UXO program. Sites must be of sufficient geographic extent to warrant a deployment given the high costs associated with mobilization and demobilization. In addition, terrain, geology, and vegetation must also be considered for such a deployment.

Extremely variable terrain or the presence of tall vegetation can greatly limit or impede the use of the airborne technology for the UXO objectives of interest. Finally, the UXO objective must be consistent with the detection limits and capabilities of the airborne system to make such a deployment feasible.

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6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

Costs were largely within the original estimates. Data acquisition, processing, and analysis tasks consumed approximately 60% of the funding. This project was able to leverage mobilization costs associated with shakedown tests to reduce the total expenditures. The project leveraged costs from other airborne survey projects being conducted on behalf of DoD to support testing the airborne EM system.

The site used for this evaluation was geologically ideal but logistically difficult. Overnight staging was done from the Rapid City Regional Airport, while day time refueling of the helicopter was done at Cuny Table by truck. In spite of this, most of the survey blocks were still tens of miles away from the base of operations. With a one-way flight time of nearly 30 minutes, this reduced the available onsite survey time to approximately 1.5 hours per flight. The ferry time between the airport and the survey site therefore represented a significant portion of the airtime.

Additional cost savings may be possible in the data processing and analysis tasks. As noted earlier, a considerable amount of time was devoted to developing or refining the processing methodology. The continued and consistent use of a static technology should reduce most of the processing procedures to a semi-automated technique. Under these conditions, rapid delivery of survey results should be possible. This really only applies to a production-oriented system. In a research platform, continued modifications to the system or new improvements to the processing methods will largely negate this benefit.

6.2 PERFORMANCE OBSERVATIONS

The primary performance objectives were largely exceeded by this demonstration. Practical survey heights were lower than expected, and the additional bandwidth in data recording allowed for much higher resolution of the seeded targets. The test grid was established with the objective of bracketing the detection capabilities of the system by placing smaller and deeper items than the previous demonstration.

The objectives of this project were to demonstrate detection of metallic targets, whether ordnance or nonordnance. No attempt was made at classification, which made ground follow-up difficult to analyze with traditional UXO techniques (probability of detection [Pd] and false positive [FP]). FPs were not calculated due to the limited nature of the data acquired. While not specifically measured, very limited ground follow-up demonstrated that there were no false negative responses associated with the demonstration survey.

6.3 SCALE-UP

Scale-up of operations could be conducted from either of two scenarios. The first scenario uses the current technology as is, with only minor modifications. The second scenario utilizes more comprehensive modifications to improve efficiency and resolution.

The current technology requires minor hardware and firmware modifications to increase the number of channels as well as to improve aircraft and data positioning. Suitable training of geophysical personnel to handle the data processing will also be required, once the methodology has been refined to a more automated process. Given the current market conditions, equipment availability should not be an issue. A single operating system should be sufficient to handle all available work for the foreseeable future. At present, qualified personnel represents the most significant obstacle.

The second option incorporates more comprehensive modifications to the system in an effort to improve efficiency and data quality. An increase in the number of receiver channels from two to eight would significantly enhance the operational performance of the system. A vertical gradient system may also provide advantages in terms of noise cancellation and sensitivity to small targets. As with the first option, a single system should be sufficient to handle current market demand, and the most significant obstacle is the shortage of qualified personnel. In addition, new processing techniques would have to be tested to handle the new data configuration.

6.4 OTHER SIGNIFICANT OBSERVATIONS

As mentioned previously, major factors in implementing or deploying the airborne system are topography and vegetation. Steep topographic variations make it difficult to achieve uniform altitude across the survey area. Most topographic features will be coherent between lines, which makes them easy to identify and will not be confused with ordnance signatures. The impact on data quality is that the average altitude will increase, making it more difficult to detect smaller objects.

Vegetation has a similar effect on data quality in that it necessitates an increase in survey altitude. Isolated pockets of vegetation or single trees can be handled in two ways. The first is to fly over them and create a small pocket of lower resolution data. The second is to fly around them and create a minor gap in data coverage. Continuous stretches of vegetation or forest should be avoided.

Geologic influence is another factor impacting the technology implementation. The difficulty of detecting ordnance in highly magnetic environments is well documented and impacts the airborne system as it would a ground system. The only recognized solution to this problem would be to develop an airborne EM system.

6.5 LESSONS LEARNED

The primary benefit of this technology is in rapid reconnaissance of large open areas, commonly referred to as footprint reduction. Cost analysis shows that costs per acre decrease significantly with the size of the project, whereas ground surveys tend to have a fixed cost per acre. It would therefore be prudent to survey as large an area as possible with each mobilization, even if all the data are not processed immediately.

6.6 END-USER ISSUES

End users have been included in the project as often as possible. The USAESCH innovative technology director is the project principal investigator, the Oglala Sioux (landowners) have been included in the project conception and preparation, and Parsons Engineering Science has conducted the ground truth in parallel to their own EE/CA activities. Private sector firms have also expressed an interest in having one or more of their geophysicists trained to handle airborne EM data. All of these parties have been supportive and encouraged by the survey results to date. In particular, the explosive ordnance disposal (EOD) technicians responsible for the excavations have expressed their admiration for the detection ability and positioning accuracy of the results.

6.7 APPROACHES TO REGULATORY COMPLIANCE AND ACCEPTANCE

It is important to recognize the different aspects associated with the regulatory involvement in both the technology and the application of the technology to a UXO-contaminated site. With regard to the application of the technology, there are issues associated with regulatory drivers and involvement of both regulatory entities and other stakeholders that are relevant.

Although no specific regulatory drivers exist at this time for UXO-contaminated land, UXO clearance is generally conducted under CERCLA authority. Additionally, a draft EPA policy is currently under review as attempts to establish a “range rule” were abandoned. Regardless of a lack of specific regulatory drivers, many DoD sites and installations are aggressively pursuing innovative technologies to address a variety of issues associated with ordnance and ordnance-related artifacts (e.g., burial sites) that resulted from weapons testing or training activities. These issues include footprint reduction and site characterization, areas of particular focus for this technology demonstration. In many cases, the prevailing concerns at these sites become a focus for the application of innovative technologies in advance of anticipated future regulatory drivers and mandates.

There are several types of sites where UXO contamination is an issue. These include closed, transferred, and transferring (CTT) ranges, such as FUDS and BRAC sites, as well as sites on active and inactive ranges that are not scheduled for closure. Where sites are designated for civilian reuse, it is important that the UXO be removed to the extent possible and that proper safeguards be established where there is any possibility that live ordnance might still be in place. It is also important that a permanent record be maintained to document all measurements that are made to support clearance activities. Advanced technology, such as the airborne system, is expected to contribute to the performance of these activities in terms of effectiveness as well as cost.

With regard to the technology itself, the only regulatory agency involved in the implementation of this technology is the FAA. Since the boom mounting structure is bolted directly to the hard-points of the aircraft, this installation becomes a modification to the airframe that requires FAA approval. These approvals were obtained in the form of an STC obtained by the aeronautics engineer at the time of manufacture. The current documentation is both time and aircraft limited to experimental flights only. Final approvals, which are unlimited in use, will follow the final design modifications.

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Appendix A
Points of Contact

Point of Contact	Organization Name and Address	Phone/Fax/Email	Role in Project
D. Scott Millhouse	U.S. Army Engineering and Support Center, Huntsville 4820 University Square Huntsville, AL	256-895-1607 256-895-1602 Scott.D.Millhouse@ HND01.usace.army.mil	USAESCH Innovative Technology Manager and Co-Principal Investigator
David T. Bell	Oak Ridge National Laboratory P.O. Box 2008 Oak Ridge, TN 37831-6038	865-574-2855 865-576-8646 belldt@ornl.gov	ORNL Project Oversight
William E. Doll	Oak Ridge National Laboratory P.O. Box 2008 Oak Ridge, TN 37831-6038	865-576-9930 865-576-8646 dollwe@ornl.gov	Principal Investigator and Geophysicist; data processing, analysis, and interpretation
T. Jeffrey Gamey	Oak Ridge National Laboratory P.O. Box 2008 Oak Ridge, TN 37831-6038	865-574-6316 865-576-8646 gameytj@ornl.gov	Geophysicist; data processing, analysis, and interpretation
Les P. Beard	Oak Ridge National Laboratory P.O. Box 2008 Oak Ridge, TN 37831-6038	865-574-4646 865-576-8646 beardlp@ornl.gov	Geophysicist; data processing, analysis, and interpretation

ESTCP Program Office

901 North Stuart Street
Suite 303
Arlington, Virginia 22203

(703) 696-2117 (Phone)
(703) 696-2114 (Fax)

e-mail: estcp@estcp.org
www.estcp.org